Holocene coastal changes in Rio de Janeiro state, Brazil

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HOLOCENE COASTAL CHANGES IN RIO DE JANEIRO STATE, BRAZIL

Thesis submitted for the Degree of Doctor of Philosophy, Durham, 1988

Abstract

Evidence of Holocene sea-level changes along the Rio de Janeiro State Coast, and for the evolution of coastal lagoons and barriers in response to these sea-level movements, has been examined using stratigraphical and micropalaeontological techniques, radiocarbon dating and published data. Present-day diatom death assemblages have been studied in order to facilitate the interpretation of fossil assemblages, which has *inter alia* permitted the development of a simple statistical technique for the evaluation of the allochthonous diatom component. Modern lagoonal tide-gauge data have been used to establish a relationship between lagoonal water levels and tidal levels on the open coast.

Evidence is presented which indicates that barriers which were previously believed to date from the mid-Holocene formed during the 'Last' Interglacial. The history of true Holocene barriers has been shown to be relatively complex, with some barriers having migrated by over-stepping and others by continous shoreface retreat. The published Holocene sea-level maximum for Rio de Janeiro State of + 4.8 m at 5100 BP is considered to be in error (approximately 3.0 m too high at this time) and a maximum Holocene sea level of + 3.0 m at *c.* 4000 BP is preferred. The evidence for sea-level maxima in other parts of Brazil at 5150 BP and for the migration of the geoid surface during the Holocene is questioned and shown to require further study. It is tentatively suggested that there may be evidence for an interglacial sea-level high at *c.* 35000 BP in Rio de Janeiro State.

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by

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Declaration

No material contained in this thesis has previously been submitted for a degree in this or any other university.

Statement of Copyright

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1. INTRODUCTION

This is principally a study of the evidence for the nature of Holocene sea-level changes along part of the Rio de Janeiro State coast. The work is confined to the evidence for coastal and sea-level changes in the present coastal zone and does not address itself to the landward migration of the coastline since the 'Last' Glacial maximum. The coastal plain between Niteròi and Ponta Negra (43°05'W and 42°45'W) was selected for the study area as reconnaissance work, carried out in 1979 by M. J. Tooley and D. Muehe, indicated that suitable sedimentary sequences were likely to be found.

1.1 Aims of the study

This study has three broad objectives which are:

a) to determine the applicability of a sea-level research methodology, which has typically been employed in temperate coastal areas with meso- and macrotidal ranges, to a tropical coastline with a microtidal range (<2m following Hayes, 1975)

b) to establish the Holocene sedimentary history of the lagoons and barriers along a homogeneous stretch of the Rio de Janeiro State coastline.

c) to identify sea-level index points and sea-level tendencies in the study area and compare the results with those obtained by earlier empirical and model-based approaches in Brazil, having critically assessed these works.

The research methodology, which employs stratigraphic analysis, micropalaeontological analyses (particularly of pollen and diatoms), plane surveying and radiocarbon dating, is the product of many years of sea-level research in Europe. It is continually evolving and being refined with notable contributions from Godwin (see Tooley, 1986), Iversen (1937), Florin (1944), Jelgersma (1961), Tooley (1978, 1982), Streif (1979), Shennan (1980, 1982a,b, 1983, 1986a,b) and Shennan *et al.* (1983). The analysis of alternating inorganic and organic facies deposited respectively in the lagoonal and tidal flat zone and the perimarine zone (in which the elevation of the water table is influenced by sea-level change) (Hageman, 1969) has been central to the work carried out to date. In Rio de Janeiro, however, the tidal range of 1.38 m has allowed the formation of barrier beach systems that isolate the lagoons completely from the ocean and permit freshwater conditions to prevail. The elevation of the water table in this perimarine zone is likely to be more strongly influenced by evaporation than in mid latitudes, so that sea level may not be a major factor influencing its water quality and level.

Most of the techniques traditionally used in this methodology have already been employed in low latitudes, but the micropalaeontological techniques which are fundamentally important to the method, setting it apart from those relying solely on the description and dating of sedimentary sequences, have not generally been used to resolve problems of the sort encountered in this study.

Muehe (1982) developed the current chronology of lagoonal and barrier formation in the study area by comparing the height of water-laid sand on the barriers with sea-level curves for São Paulo State and southern Rio de Janeiro State (Suguio and Martin, 1981). This chronology is possibly in error on at least two counts : firstly, the sea-level curves may not be applicable to the study area; and secondly, Muehe relates the high point of the barrier to the curve which (as this is unlikely to represent the height of the barrier at formation) only indicates that the barrier was in existence for an unspecified time before the derived date. Furthermore, the existing chronology is crude, giving no indication of the stability of the barriers over time, nor indicating when they adopted their present closed form.

The extent of existing and proposed housing development along these barriers makes it important to know more about the behaviour of the barriers.

There is a need for sea-level data in Rio de Janeiro State as it is relatively little studied, unlike the States of São Paulo and Bahia. There are only 26 index points for Rio de Janeiro State and 24 of these are from the southern Baía da Ilha Grande and Baía de Sepetiba region. This compares with 57 index points for São Paulo and with 121 index points for Bahia, not including archaeologically derived dates.

1.2 The Rio de Janeiro State coast.

The southern coastline of Rio de Janeiro State (Figure 1.1) is characterized in the east by numerous lagoons, separated from each other by crystalline headlands and backed by steeply rising crystalline massifs and inselbergs, and in the west by the bays of Ilha Grande and Sepetiba. The eastern coast, north of Cabo Frio, has few lagoons larger than 1 km^2 and is characterized by the delta of the Rio de Paraíba do Sul and by the eastern extreme of the Guanabara Rift.

The crystalline basement was completely consolidated early in the Brazilian Cycle (450-700 ma), the last of three major Precambrian geotectonic cycles which greatly influenced the geology of Brazil. In Rio de Janeiro, the basement is composed of metamorphic rocks ranging from amphibolites to granulites and of intrusive granites, all of the Brazilian Cycle. These lie in the Southeast or Ribeira Folded Belt, (Almeida *et al.*, 1973) one of several

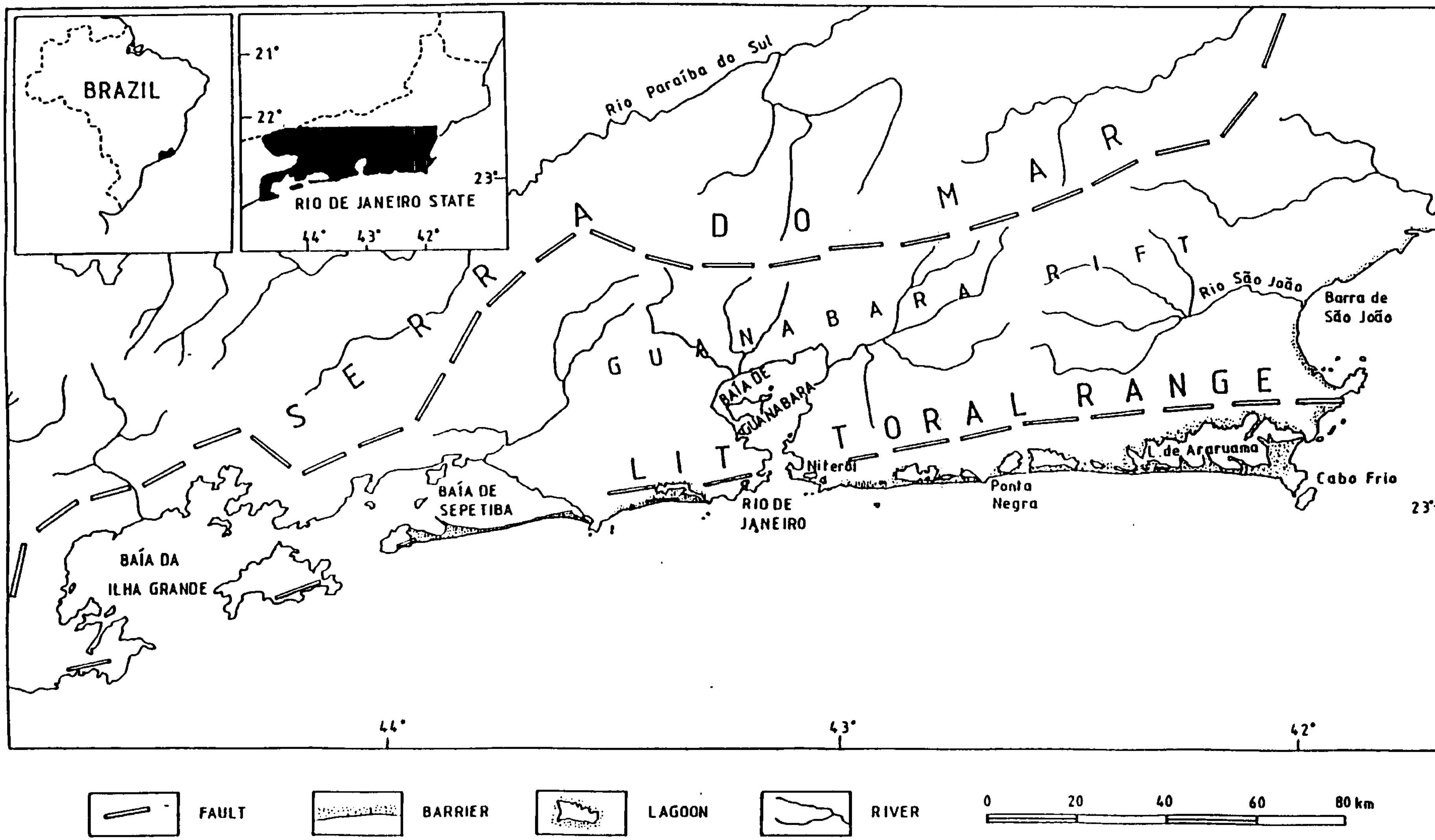


Figure 1.1 A map of the southern part of Rio de Janeiro State, with inset maps of Brazil and the State of Rio de Janeiro

belts of folding found throughout Brazil which are characteristic of this cycle. Intense Brazilian faulting followed the folding, with large transcurrent faults (trending mostly ENE) obliquely crossing the Precambrian structures which generally trend NE to ENE (Almeida, 1976).

This activity was followed by a period of tectonic stability which lasted until the Jurassic when a tectono-magmatic reactivation, the South Atlantic Event, occurred. This event, formerly known as the Wealdian Reactivation (Almeida, 1976) but redesignated by Schobbenhaus and Campos (1984), marks the split of the South American and African continents.

At this time Brazilian faults were reactivated (Campos *et al.* 1974; Almeida, 1976) establishing the general configuration of the continental margin. The configuration in southern Rio de Janeiro is unusual because a large part of the coastline, between Baía da Ilha Grande and Cabo Frio, has an east-west orientation; the only part of the Brazilian coast south of Cabo de São Roque (Rio Grande do Norte) so oriented.

The first marine transgression occurred in the Aptian, as the continents continued to drift apart, with full marine conditions in the Albian (Ojeda, 1982). Many of the fault systems which developed rift valleys and asymmetric rifts in the early taphrogeny were later rejuvenated by progressive subsidence and seaward tilting of the continental margin (Campos *et al.*, 1974).

An example of such a rejuvenated rift valley is the Guanabara Rift, which is between 25 and 30 km wide and at least 200 km long. It extends from Barra de São João in the east to Sepetiba in the southwest and possibly includes Baía da Ilha Grande. It probably formed in the Oligocene, but assumed its modern aspect in the Pliocene when its relief was accentuated. Almeida

(1976) states that seismic activity in the region, although weak, seems to indicate that the rift system is not entirely inactive.

The northern border of the rift is formed by the dissected, stepped escarpment of the Serra do Mar, known locally as the Serra dos Orgãos, which reaches a maximum altitude of 2263 m (Pedra do Sino). There is a sharp transition between the escarpment and the plain of the rift floor. To the north, this range slopes gradually into the valley of the Rio de Paraíba do Sul.

The southern border of the Guanabara Rift is formed by the faulted blocks of the littoral massifs. These are inclined towards the north and have steep southern escarpments which back the present narrow coastal zone. The escarpments have been dissected by river valleys, and weathered and eroded to form characteristic isolated peaks with steep, rocky, bare walls. Ruellan (1944) distinguishes between the massifs to the west of Baía de Guanabara and those of the east. Those to the west of the bay, which Ruellan (1944) describes as a ria, have a mean altitude of 800 to 900 m with a maximum of 1024 m (Pedra Branca). The massifs to the east are lower, in particular those of the Niterói Range reaching only 400-600 m. Locally, in the Serra de Mato Grosso, they reach 889 m but altitudes of over 500 m are rarer than in the west.

In the narrow coastal zone there are over 40 Holocene lagoons (*lagoas*). They range greatly in size, with over 20 covering more than 100 ha and a similar number covering only a few hectares. The largest lagoon is Lagoa de Araruama which covers about 20,000 ha with a mean depth of 3 m, but such large lagoons are the exception, with only Lagoa de Araruama and Lagoa Feia of this order. Some lagoons, like those in the Maricá and Jacarepaguá Systems, are interconnected forming larger water bodies. In the Maricá

System there are five lagoons ranging in size from 120 ha to 1849 ha with the system as a whole covering 4000 ha and having a catchment of 27000 ha (Oliveira *et al.*, 1955a,b). This compares with Lagoa de Rodrigo Freitas, a single lagoon with a surface area of 230 ha and a catchment of 2000 ha (Brito and Lemos, 1982). The lagoons are confined on their seaward sides by *restingas* - coastal linear barriers of sand which remain exposed, even at high tide.

There are three types of lagoon which can be identified in this area:

Firstly, there are lagoons formed by a *restinga* developing across the mouth of a bay. Such lagoons range from simple rounded forms like Lagoa de Itaipú to complex shaped systems such as the Maricá System. These are most common along the southern coast and are generally confined on the landward by the Littoral Range and pre-Holocene sedimentary sequences (Figure 1.2).

Secondly, there are lagoons, elongated parallel to the coast, formed between two *restingas*. These vary greatly in size with most covering only a few hectares. Lagoa de Marapendi (Figure 1.2) is the largest example. Lagoons, or former lagoons, of this type are found along the entire coast from Baía de Sepetiba to the mouth of the Rio Paraíba do Sul.

Thirdly, there are lagoons formed by *restingas* enclosing the drowned mouths of river valleys. These are infrequent along the entire coast. In the south this is probably because the few rivers which flowed into the Atlantic had their mouths within embayments which became lagoons of the first type. Rio Preto, east of Visqueiro, on the eastern coast is an example of such a lagoon and Rio Itacáia, Itaipu-Açu, was formerly a small example of this type of lagoon.

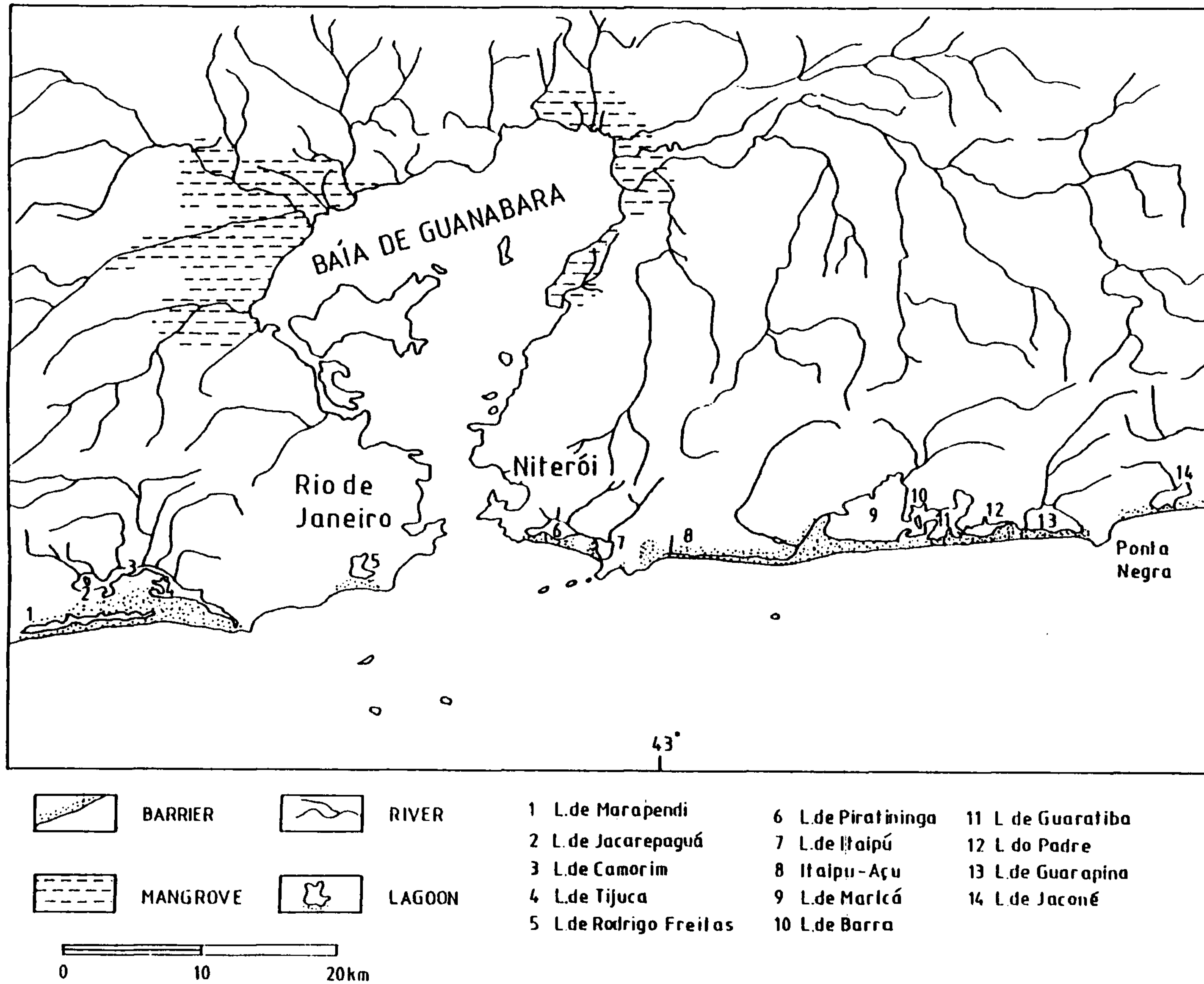


Figure 1.2 A map of the coastal lagoons bordering Baía de Guanabara, Rio de Janeiro State

The *restingas* which isolate the lagoons of Rio de Janeiro were interpreted as a series of spits and tombolos by Lamego (1945). They were presumed to have been built out across bays by longshore currents flowing from west to east, the material being provided predominantly by rivers. Between Itaipu-Açu and Ponta Negra, for example, (a distance of approximately 34 km) a single spit was identified. Later analysis (Muehe, 1979) showed that the grain size of beach sand decreases towards the east, which seems to support the spit-building hypothesis.

Muehe (1982) argued, however, that the *restingas* are barrier beaches formed by the submergence of beach ridges, following the explanations of Hoyt (1967) and Swift (1975). The sediment which forms them originated offshore with little contribution from modern continentally derived sediments. A high proportion of polished rounded grains, characteristic of submarine reworking, were found and the decrease in grain size along the *restinga* is attributed to differences in offshore sediment grain size (Muehe and Barbosa, 1982; Muehe, 1982).

Muehe's evidence is persuasive and negates the hypothesis proposed by Lamego, but the history of barrier beach formation may be more complex. Schwartz (1971), following Chamberlin's (1965) method of multiple working hypotheses, advocated the adoption of the principle of multiple causality of barrier formation. Tentatively he proposed that engulfed beach ridges generally form primary barriers, and that spits or emergent offshore bars form secondary barriers. Composite barriers are formed by a combination of two or more of the above processes. Along this coast there are single barriers, barriers formed by the merging of two, once distinct barriers and double barriers which are either separated by a narrow water body or simply divided by a depression. Thus, following Schwartz (1971), it is possible that more than one process is involved.

Figueiredo (1980) discussed the origin and maintenance of sand ridges on the inner continental shelf of southern Brazil. The hypothesis that these ridges are remnant features formed during low-stands of sea level is rejected in favour of the ridges being formed as a consequence of storm winds forcing the coastal waters which in turn displace bottom sediment. The sediment is eroded from troughs and deposited on ridge crests. This work illustrates that offshore bars may form independently of sea-level movement. Such ridges may be considered as a potential origin of secondary barriers and as a contributory factor to composite barrier formation.

The possibility that spits may form part of the present barrier system should also be considered. Emmerling and Tanner (1978) showed that longshore drift was occurring in opposing directions along the beaches of Piratininga and Itaipú. The beaches are short compared to others in the area and so possibly not representative, but it is clear that sands of submarine origin are being at least partially reworked by littoral currents. The extent to which this has occurred is unclear, but the fact that the lowest points (*lidos*) of their barriers are the furthest points from the origin of the longshore currents may be significant.

The *lidos* are described by Oliveira (1948) as low points over which sea water passes at highest astronomical tide. Historically the *lidos* have been deepened by fishermen to allow lagoonal and coastal waters to mix and encourage marine/brackish fish stocks to be replenished. This is now a rare event (Anonymous, 1983).

There are marked differences in the altitudes of the barriers. Between Niterói and Ponta Negra, the maximum altitudes of present-day barriers (single and merged) vary between 4.0 and 10.0 m and the maximum altitudes of fossil barriers from 7.0 to 12.2 m (Muehe, 1982). There is a positive correlation between barrier height and median sediment size for all beaches between Niterói and Cabo Frio (Muehe, 1979). The coarsest sediment and highest barrier is found at Itaipu-Açu.

The crystalline mountains and headlands, whether deeply weathered or fresh rock outcrop, the waters of the lagoons, the surrounding marshes and the *restingas* are all vegetated with a rich flora. Gardner (1840), then Director of the Royal Botanic Garden, Ceylon, was struck by the diversity of the vegetation:

> *"There is perhaps, no part of the world where, in an equal extent of country, a greater variety of vegetable forms are to be met with more than in the province of Rio de Janeiro..."*

In the sixteenth century dense climax rainforest covered about 97% of Rio de Janeiro State, but in the eighteenth century the littoral region was developed as a sugar cane producing area and by the start of the nineteenth century most of the lowland forest had been destroyed. During the nineteenth century much of the mountain forest was removed to make way for coffee production, which after abandonment frequently developed into secondary forest (Araujo and Vicaça, 1981). Today, even the *restinga* vegetation, which had survived intact until the middle of this century, is being destroyed by property development and marsh areas are being modified by drainage and cattle and horse grazing.

Araujo and Vicaça (1981) indicated that it is now impossible to reconstruct the composition of the forests which covered the littoral mountains because the literature only contains generalized descriptions of this vegetation. According to Gardner (1840) the forest trees on the mountains near Rio were dominated by different species of *Ficus*, *Bombax*, *Cassia*, *Lecythis*, *Bignonia*, *Swartzia* and *Myristica* together with genera from the families of Myrtaceae and Melastomataceae. Dansereau (1948) on the other hand described, *Lecythis*, *Aspidosperma*, *Vochysia*, *Ouratea*, *Cabralea*, *Cariniana*, *Cedrela* and *Nectandra* as climax trees. Arauju and Vicaça (1981) surveyed the vegetation of Morro das Andorinhas, a low headland of 190 m, which lies immediately east of Lagoa de Itaipú. They recorded 99 species from 63 families, including species characteristic of the Atlantic forest and elements of the *restinga* vegetation.

According to Dansereau (1948) the structure of the coastal rainforest is distinguished from that of the Amazonian forests by the absence, or rarity, of buttressed trees, by the relative scarcity of lianas and woody epiphytes and by the abundance of herbaceous epiphytes. The structure and much of the composition of the coastal forest is not thought to vary considerably from sea level to almost 1500 metres.

The flora of the lagoons varies according to the salinity regime of the lagoonal waters. Relatively freshwater lagoons are colonized by *Eichornia crassipes*, *Salvinia radula*, *S. auriculata* and *Lemna montevidensis* (Dansereau, 1947). Brackish lagoons such as Itaipú and Piratininga are dominated by *Ruppia maritima* and *Chara maritima*, with *Eichornia crassipes* close to the mouth of streams (Oliveira, 1948). The vegetation of the waters of highly saline lagoons, such as Lagoa de Araruama, is very limited (Dansereau, 1947). The lagoons are also rich in filamentous algae such as *Spirogyra* sp. and in diatoms (Oliveira, 1948).

Around the shores of the lagoons *Typha dominguensis*, *Acrostichium aureum* and *Hibiscus tilaceus* are often found in successive zones. In addition, there may be extensive areas of marshland. Brackish to saline marshes are frequently colonized by *Spartina brasiliensis* and freshwater marshes by

Cyperus giganteus (Dansereau 1947, 1950). These are all potential peat-forming species.

The vegetation of the *restinga* is very varied and largely xerophytic. Darwin travelled along the *restingas* near Maricá on 9 April 1832 and made the following entry in his Journal (Darwin, 1839).

> *"The road passed through a narrow sandy plain lying between the sea and the interior salt lagoons. The number of beautiful fishing birds, such as egrets and cranes, and the succulent plants assuming most fantastical forms, gave to the scene an interest which it would not otherwise have possessed. The few stunted trees were loaded with parasitical plants, among which the beauty and delicious fragrance of some of the orchidæ were most to be admired."*

On the beach, low succulents such as *Philoxerus portulacoides* and *Alternathera maritima* are found together with other xerophytic vegetation such as *Remirea maritima*. These give way to foredune and dune vegetation in distinctive zones. Small low shrubs such as *Sophora tomentosa* and *Eugenia uniflora* appear for the first time on the foredune. Bare sand is very evident with vegetation, dominated by *Spartina ciliata*, covering approximately 20% of the ground surface.

Where there are fossil *restingas* these are colonized by shrubs such as *Naranthea brasilienisis*, *Myrrhinium atropurpureum*, *Byrsonima sericea* and *Schinus terenbinthifolius*, together with cacti like *Mediocactus coccineus* and *Cereus pernambucensis*. Bromeliaceae such as *Neoregelia ementa*, and Araceae like *Philodendron corcovadensis* are also present. These form dense, almost impenetrable stands, separated by open sand with ground-hugging vegetation like *Stachytarpheta schottiana*. Trees such as *Ficus tormentella* and *Clusia fluminensis* appear in inter-barrier depressions and on the lagoon-ward side of the fossil *restingas*.

The vegetation of the *restingas* plays an important stabilizing role through its influence on dune formation. Kahn and Roberts (1982) showed that dunes play an important role in reducing overwash during storm events, resulting in relatively stable barrier systems.

Mangroves are relatively scarce along the east-west trending coast bordering Baía de Guanabara, but are common within the bay and elsewhere in the state, for example in Baía de Sepetiba (Zaninetti *et al.*, 1977). Three species occur along this coast: *Rhizophora mangle*, *Avicennia tomentosa* and *Laguncularia racemosa*. They form district zones with *R. mangle* occupying the most seaward position and *L. racemosa* the most landward (Dansereau, 1947). These species may appear in open lagoons, as today at Itaipú, where all have recently colonized parts of the lagoon's shore, after the construction of an artificial channel between it and the ocean.

2. TECHNIQUES

2.1 Introduction

Essentially all the techniques used in this study are commonly employed in the study of sea-level change. The detailed application of such techniques, however, varies considerably especially on tropical coasts, so it is necessary to describe precisely the methods used. Techniques which have a more standard application are described in less detail.

2.2 Sedimentary analysis

Three techniques have been applied to the analysis of the sediments of the Rio de Janeiro State littoral: stratigraphic analysis, particle size analysis and roundness analysis.

2.2.1 Stratigraphic analysis

Stratigraphic analysis is an extremely important part of any study of this kind for, as Tooley (1981) pointed out, the quality of the environmental reconstruction can only be as good as the raw data collected in the field.

> *"Poor quality data at this stage will jeopardise the validity of any conclusions based both on these data and subsequent analysis."*

The equipment used to extract cores of unconsolidated sediment was a modified Eijkelkamp hand operated *puls* auger set for heterogeneous soils (Eijkelkamp, 1981). The maximum reach of the set was extended from 7.25 to 11.25 m because a limited amount of engineering borehole data suggested that this depth of unconsolidated sediment would be encountered. Only combination and sand-type Edelman augers were included and, to facilitate the uncompressed extrusion of cores, a liner sampler was added. The set can be divided into augers which take the required, virtually undisturbed samples and supplementary equipment. There are three augers which take largely undisturbed samples; these are the gouge, the suction and the liner.

The gouge auger (Eijkelkamp, 1984; Tooley, 1981) consolidates the core slightly but is efficient and reliable when sampling most organic and fine grained inorganic sediments. It samples fibrous, unhumified peat poorly and is not suitable for sampling highly cohesive sediment or very stiff clay. From 3 September 1982 a different gouge sampler was used. This was made, to the author's specification, by Mechanica Stubbs of Rio de Janeiro. The new auger was longer (1.0 m rather 0.5 m) and had a slightly narrower chamber which proved more effective at retaining sediment.

A suction auger, as described by Eijkelkamp (1981), can only be applied to moderately cohesive sediment (sand, well humified organic matter and uncompacted silt and clay) below the groundwater table. It takes only slightly disturbed samples so, while any structure may be lost, the size distribution of the sediment is preserved. Also, because the chamber is closed until sampling, contamination problems are reduced. The only problem with this sampler arises when stiff clay enters the chamber. It may enter very easily, but is extremely difficult to remove.

The liner sampler is a 25 cm long cylinder in which plastic liners are held in place by the cutting edge. The liner can be pulled out of the cylinder after sampling, thus eliminating compaction during extraction. The cutting edge was frequently lost when sampling, so the retaining screws had to be modified. Generally it was not very effective as complete cores were rarely recovered. It only performed well in cohesive soils above the water table and even the length of the chamber was too short to be efficient. This sampler was consequently used very infrequently.

The supplementary equipment consists of handles and extension rods for the augers, plastic casing tubes with accessories, soil augers to pre-auger up to the groundwater table, so allowing the casing to be used and a bailer (or *puls*) together with Edelman and other soil augers to remove sediment from within the casing to the required depth for sampling with the gouge or suction auger.

When sampling at depth some curvature of the extension rods is inevitable, resulting in incorrect depth measurements. This can be minimized by disconnecting rods as the equipment is withdrawn. Another problem, associated with the open chamber samplers, is contamination which can result from curved extension rods being connected in a different sequence each time a sample is taken, or from sediment filling the augered hole through expansion, seepage or slumping due to lack of casing. The former can be avoided by always connecting the rods in the same order and always orienting the chamber in the same direction. The latter is minimized if all slumped material is removed with the auger or bailer, before sampling the next half metre or metre.

The sediment is described, and the symbols used in the figures are drawn, according to the scheme proposed by Troels-Smith (1955). This scheme should be purely descriptive, but has been criticized (Shennan, 1980) on the grounds that *Limus humosus* cannot be identified simply by its properties; interpretation is required. Thus to ensure a purely descriptive field record, the term *Limus humosus* will not be used and *Substantia humosa* will be used in all cases to describe completely, or nearly, decomposed organic substances without macroscopic structure.

The scheme, as described by Troels-Smith (1955), does not include mineral particles coarser than 20 mm (*Grana glareosa* (*majora*)), so coarse gravel (20 to 60 mm) is described as *Grana glareosa (maxima)*, which is abbreviated to Gg (max.). Gg (max.) is distinguished from Gg (maj.) in the figures by the use of a thicker line; the circle is the same diameter.

The statigraphic descriptions are presented in a standard format, following Tooley (1978); each stratum is numbered, the height of the stratum in relation to the national datum (Imbituba, Santa Catarina) is given in metres, the depth of the stratum from the surface is given in metres and the sediment is described both in abbreviated formula, following Troels-Smith (1955), and in prose.

The first line of the abbreviated formula lists the component elements, their proportions and the degree of humification of any *in situ* organic matter. The physical characteristics of darkness (*nigror* = nig.), stratification (*stratificatio* = strf.), elasticity (*elasticitas* = elas.) and dryness (*siccitas* = sicc.) are listed on the second line. On the third line colour (*color* = color), which is described using the 1954 edition of the *Munsell Soil Color Charts*, and structure (*structura* = struc.) are recorded. Finally the sharpness of the upper boundary of the stratum (*limes superior* = lim. sup.) is described.

There are three major sources of error when this scheme is applied:

a) identification of a stratum boundary - it is impossible to identify the boundary position in a consistent way when the components of the sediment change gradually.

b) identification of the elements - trace elements, in particular, may be overlooked.

c) assessment of the proportions of the elements - this can be difficult in silty clayey sediment and is necessarily inaccurate when there are equal parts of three elements, because the frequency scale is four pointed.

Errors ranging from those caused by rod curvature to those of boundary identification are all compounded to produce altitudinal errors. Heyworth and Kidson (1982) estimated that at a depth of 30 m an uncertainty of ± 10 cm is probably involved because of errors introduced by boring, sampling and measuring procedures. Shennan (1980, 1982a) made a more detailed assessment for the UK Fenland. Estimates included: identification of boundary ± 0.01 m; measurement of depth (hand coring) ± 0.01 m; use of gouge sampler, up to - 0.20 m; angle of borehole, up to + 0.04 m.

The errors generated by using the equipment and techniques described here in Rio de Janeiro State have been estimated and are listed in Table 2.1

Table 2.1: Altitudinal error resulting from the use of stratigraphic analysis

Source of error	Error
angle of borehole	up to + 0.03m
curvature of sampling rods	up to + 0.01m
identification of boundary	up to ± 0.01m
measurement of depth	± 0.01m
compaction and extrusion with suction sampler	up to + 0.03m
use of gouge sampler	up to ± 0.08m

(calculated independently of Shennan, 1982). The assessment of the effect of an angled borehole is based upon an assumed maximum departure from the vertical of 5° which will produce the quoted error at a depth of 10 m. For curvature, a maximum departure from the vertical of 0.20 m in 10 m is assumed. The error introduced by boundary identification varies with the nature of the boundary; for a *limes* 4 boundary it would be ± 0.5 mm, for a *limes* 1 boundary, ± 0.01 m and for a *limes* 0 boundary >0.01 m. The *limes* 1 figure is quoted because this is the greatest error attributable to an organic/inorganic boundary in the study area. Compaction of >0.03 m occurred at one site when pure clay entered the cyclinder at the base of the borehole, but this only affected the bottom 75 cm which as discarded.

Shennan (1980, 1982a) quoted a large error of up to - 0.20 m associated with the use of the gouge sampler, but an error of this magnitude is not borne out by the limited evidence from this study. The altitudes of boundaries between peat and clastic sediment on one well defined peat stratum were sampled in close proximity (a distance of 1 m) with a gouge and suction sampler at several locations. The altitudinal discrepancies of the gouge were as follows: - 0.01, - 0.08, +0.04, +0.03, 0.00 and + 0.01 m. Thus a maximum of ± 0.08 m is quoted in the table, but some of the discrepancy could result from other factors listed in the table.

At all sites sampling was completed before any representative cores for use in further analysis were taken. These cores were sampled with the suction sampler and the sediment placed in 25 cm lengths of plastic tubing which had been split longitudinally. The tubes were sealed in polythene and carefully packed for air freighting to England. Six months elapsed between sampling and shipment of the sediment, during which time the samples were stored in a cool room. On arrival in Durham they were placed in a cold room at 0° centigrade.

2.2.2 Particle size analysis

Originally it was hoped to utilize particle size analysis in this study to identify sedimentary environments adopting the parameters detailed by

Folk (1966). However, while these have been applied on many occasions (Folk and Ward, 1957; Shepard and Young, 1961; Davis and Ehrlich, 1970; Poncano and Fulfaro, 1978; Wilson *et al.*, 1981), the attempts to determine accurately depositional environments have been only partially successful. Reineck and Singh (1980) suggest that there are three main reasons for this.

a) The hydrodynamic factors which produce the particle size distribution are not confined to specific environments; similar factors can occur in different environments and produce comparable distributions.

b) The availability of material of particular particle size and the scarcity of other grain sizes can distort the form of expected distributions.

c) The origin of the material, whether bedrock or unconsolidated sediment, and the proximity of the site of deposition to the source can also greatly influence distributions.

Furthermore, in order to produce statistically valid results using these parameters it is necessary to analyse many samples per stratum and this is not possible with a sampling strategy which takes only one or two cores per site for detailed laboratory investigation.

The only sizeable body of particle size data is the relatively coarse breakdown, by class, provided by the Troels-Smith field descriptions. These data are, none the less, sufficient to distinguish between high and low energy environments at the time of deposition and to determine the relative roles of suspension, saltation and rolling. In this study, therefore, particle size analysis is used primarily to validate the field records based on Troels-Smith descriptions and to establish any investigator bias.

In order to carry out this validation process it is not necessary to use $\frac{1}{4}$ to $\frac{1}{2}$ phi sieve-size intervals, because by using the British Standards Institute particle size classification (BS 1377, 1967) and the sieves recommended in the pipette method, which correspond to the Troels-Smith (1955) classification (Table 2.2), a direct comparison is provided.

Table: 2.2: A comparison of the Troels-Smith sediment classification with the British Standards Institute grain-size classification

British Standards test sieves	Grain size (mm)	British Standards Institute grain - size classification	Troels-Smith classification
	<0.002	clay	*Argilla steatodes* (As)
	0.002-0.06	silt	*Argilla granosa* (Ag)
200 (0.075mm)	0.06 - 0.2	fine sand	*Grana arenosa* (Ga)
72 (0.21mm)	0.2 - 0.6	medium sand	*Grana arenosa* (Ga)
25 (0.06mm)	0.6 - 2.0	coarse sand	*Grana saburralia* (Gs)
7 (2.4mm)	2.0 - 6.0	fine gravel	*Grana glareosa minora* (Gg (min.))
$\frac{1}{4}$ in (6mm)	6.0 - 20.0	medium gravel	*Grana glareosa majora* (Gg (maj.))
$\frac{3}{4}$in (20mm)	20.0 - 60.0	coarse gravel	*Grana glareosa maxima*[1] (Gg (max.))

[1] This division of the *Grana glareosa* has been added to describe coarse gravel

Samples for analysis were not taken at regular intervals, as this could have led to the mixing of distinct strata. Rather, samples were taken from within each stratum identified in the field. In all cases they were removed after completion of the diatom analysis and the number of samples per stratum varied according to its thickness. The sample thickness was 4 cm, unless this was greater than the extent of the stratum in which case the sample size was equal to the stratum thickness.

The sediment was analysed by the pipette method (test 7c - BS 1377, 1967) using a specific gravity of 2.65. British Standard $\frac{3}{4}$ in (20 mm) and $\frac{1}{4}$ in (6 mm) test sieves were used in addition to those recommended for this method, and a mechanical sieve shaker was employed. The additional sieves were used to extend the method, which covers the quantitative determination of the particle size distribution in sediments up to coarse sand size, to include gravel. BS 1377 (1967) describes the test as inappropriate if $<10\%$ of material passes the No 200 test sieve, but the results will still provide a valid test of the field descriptions. When $<10\%$ of material passes this sieve, which is true of 25% of the samples tested, the subdivision of the silt and clay fractions should be considered unreliable. The results will be presented in tabular form to the nearest 0.01%.

2.2.3 Roundness analysis

The roundness of particles is a measure of the sharpness of their edges and corners and is independent of their shape (Powers, 1953). Reineck and Singh (1980) state that roundness parameters do not provide any direct clues to the nature of depositional environments, but several workers including Beal and Shepard (1956) and Waskom (1958) have successfully characterized certain environments. Waskom, working in Florida, showed that sands (0.208 mm to 0.043 mm) from certain environments have distinctive roundness patterns. In all size fractions examined, beach ridge environments had a high degree of roundness and marsh environments a low degree, while most other environments ranged from high to low.

Because of the interpretational uncertainty of the technique, it was considered inappropriate to carry out this type of analysis at all sites. At Lagoa do Padre site 1, however, an additional interpretational aid was required to provide more information about the depositional environments of several diatom-poor, sandy strata. Therefore, Powers (1953) roundness scale and methodology were used to characterize sand in each of the BS particle size categories isolated through particle size analysis of core LP-1/32. Fifty or more grains from each size category were classified according to the scale and the mineral type recorded.

In order to interpret the results more accurately, samples from modern sedimentary environments should be analysed and compared with the ancient samples. This could not be done because, at the time of field sampling, the use of this technique was not anticipated and no modern analogues were collected.

2.3 Levelling

All sample sites have been levelled to the Brazilian national vertical datum, which is mean sea level (MSL), Imbituba, Santa Catarina State. This is 23 cm above MSL-Ilha Fiscal (The tidal gauge located in Baía de Guanabara). A MOM Ni-B3 level and folding staff were used.

In Brazil, there is no system comparable to that of the UK, with comprehensive cover of benchmarks, related to the national datum and established by the national survey authority. The *referencia de nivel* (RN) which exist have been established by different organizations often to satisfy a particular local requirement, so, for example, some RN in the study area have been levelled by the Superintendência Estadual de Rios e Lagoas (SERLA) and others by the Fundação para o Desenvolvimento da Região Metropolitana do Rio de Janeiro (FUNDREM). It was necessary to visit the SERLA offices to obtain details of the location and reduced levels of their RN in the area.

The RN take the form of small concrete posts into the top of which are set small metal plaques. Sometimes the reduced level is related to the surface of the plaque and sometimes to a nipple in its centre. The posts are protected by law, but many have been damaged or destroyed. Indeed between 1982 and

Table 2.3: Details of the *referencia de nivel* used at each site and the closing errors recorded

Site	Authority	Reference	UTM grid reference	Altitude (m)	Closing error (m)
Lagoa de Itaipú - 1	-	RN-ESE B22A	PQ02236031	+ 3.892	- 0.006
Lagoa de Itaipú - 2	FUNDREM	RN-1010L6	NQ99525989	+ 7.637	- 0.005
Itaipu -Açu - 1	FUNDREM	RN-1010L3	PQ12685837	+ 9.618	N/A
Itaipu -Açu - 2	FUNDREM	RN-1010L3	PQ12685837	+ 9.618	N/A
Lagoa do Padre-1	SERLA	4P	PQ29385971	+ 8.376	- 0.029
Lagoa do Padre-2	SERLA	1P	PQ26985978	+ 2.884	+ 0.012
L. de Guaratiba - 1	SERLA	1P	PQ26985978	+ 2.884	+ 0.012

1983, two of the five RN used in the study were destroyed. One SERLA RN was actually dug up inadvertantly by a SERLA workman. Conveniently positioned RN were found near several sites, but it was not possible to determine their respective reduced levels as the organizations responsible for the levelling could not be traced. Details of the RN used in the study are shown in Table 2.3. Because the RN have been established by different organizations it has not been possible to ascertain the accuracy of the relationship between the RN used in this study and MSL Imbituba. However, in all but one case the quality of the levelling between RN and boreholes was assessed by closing on the originating RN. The maximum recorded closing error was 2.9 cm over 3.4 km. At Itaipu-Açu the distance involved (7.2 km between RN and site) made closing impracticable, but operator error was minimized because two people read each sight independently.

2.4 Micropalaeontological Analysis

Two techniques, pollen analysis and diatom analysis, have been used in the application of this research methodology in Europe. Pollen analysis, which has traditionally been employed most frequently, is used to indicate vegetational changes consequent upon water-level and climatic changes and, most importantly, to provide an independent relative age determination. It is not clear whether pollen analysis can be used in a similar way in the lowland tropics.

Vegetation changes of coarse resolution, which are consequent upon sea-level changes have been identified from pollen analysis in South American coastal areas dominated by mangroves (van der Hammen, 1963, 1974; Roeleveld, 1969 and Roeleveld and van Loon, 1979). Such changes have, however, yet to be identified in areas which lack mangrove swamp, but

Tooley (1986), based on the work of Dansereau (1947) and Klein (1975), believes that the coastal vegetation succession in São Paulo and Rio de Janeiro States offers similar potential. In the tidal flat and lagoonal zone of the present study area, it is unclear what type of pollen succession would result from sea-level changes. At present many of the lagoons are backed by cliffs or by inselbergs, vegetated, now or formerly, by rainforest and beyond the influence of Holocene sea-level change. The marsh areas are relatively restricted with mangroves rarely present and there is well developed barrier vegetation. Much remains to be done on the pollen taxonomy of coastal plant taxa and on pollen taphonomy.

A disadvantage of employing pollen analysis at present is that a chronology of regionally synchronous vegetation changes has not been established in Brazil. In order to provide such an independent age determination for Holocene sea-level movements, synchronous regional changes in the forest canopy must have occurred, it may not be possible to identify them using pollen analysis because of problems of recognizing the regional component of tropical pollen assemblages. Muller (1965) and Flenley (1973) found that lateral movement of pollen was restricted and that the assemblage was dominated by local trees. This factor coupled with relatively low pollen productivity and the fact that grains can frequently only be identified to family or generic level, suggests that the use of pollen analytical results to provide relative age determinations will not be possible.

Further, as stated earlier, Araujo and Vicaça (1981) have suggested that it is now impossible for the composition of the littoral rainforests to be determined. During the past 200 years the nature of the coastal vegetation has changed beyond all recognition, so it may now be very difficult to collect appropriate type material to enable fossil pollen taxa to be identified.

The task firstly of collecting type material and producing a comprehensive key to the pollen taxa of coastal Rio de Janeiro State, then secondly, analysing fossil pollen assemblages on a spatial and temporal scale sufficient to establish whether any regional trends can be identified is formidable. It has proved beyond the scope of this study.

The applicability of pollen analysis to tropical sea-level studies contrasts strongly with that of diatom analysis which has proved to be extremely valuable. The only potential problem was the identification of valves to species level, especially in the case of freshwater taxa. This, however, proved not to be problematical as many species are also found in temperate regions and, unlike pollen, tropical diatoms, including those of Brazil, have been relatively well studied.

2.4.1 Diatom analysis

Brazilian diatoms were studied in the early twentieth century by Zimmerman (1913, 1914, 1915a,b, 1916a,b, 1917, 1918a,b,c, 1919), whose contributions were mostly species lists but also contained figures and taxonomic descriptions of new species. Other works on Brazilian diatoms (Faria and Cunha, 1917; Cunha and Fonseca, 1918; Abreu, 1939; Patrick, 1944; Leprevost, 1948; Carvalho, 1950; Muller-Melchers, 1955, 1957; Andrade and Teixeira, 1957; Teixeira and Kutner, 1961) range from photographs of undetermined diatoms (Leprevost, 1948) to detailed taxonomic studies (Patrick, 1944; Andrade and Teixeira, 1957). Fossil or sub-fossil diatoms were not examined and the studies were not applied. Such applied studies are still rare; Petri and Suguio (1973) in their study of the stratigraphy of the Iguape - Cananéia lagoonal region of São Paulo State identified fossil diatoms, but listed only seven species and placed little emphasis on their value in the interpretation of coastal sedimentary sequences. Kurt Graf (1975), commenting on the paper presented by Jost *et al.* (1975) to the First Argentinian Congress of Palaeontology and Biostratigraphy, suggested that diatom analysis could be used to verify the sedimentary history they proposed for the Laguna Mirim region of southeast Brazil. This suggestion has, however, not been adopted by Jost or by others studying coastal sequences in Brazil.

This situation contrasts strongly with that in Europe where there is a relatively long history of using diatom analysis in sea-level studies. In the twentieth century, such works include Halden (1931), Iversen (1937), Florin (1944), du Saar (1969), Digerfeldt (1975a,b), Shennan (1980, 1986a,b), Kjemperud (1981a, 1981b), Haggart (1982, 1987) and Robinson (1982). Other applied studies are also common in Europe and some parts of the American continent (Bradbury, 1971; Burckle, 1972; Digerfeldt, 1975b; Ritchie and Koivo, 1975; Battarbee, 1978, 1984).

Despite this long history, there is a disagreement about the type of analysis which is most suitable for the study of fossil diatom assemblages. Andrews (1972), for example, argued that quantitative studies have limited validity and favoured a relative abundance method in which species are described as dominant, abundant, common, frequent or rare. Battarbee (1973), on the other hand, proposed a diatom concentration technique in which the absolute volumes of each taxon per cm^2 per year can be calculated. The most commonly used technique is the relative method, described by Battarbee (1979, 1986), which closely resembles relative pollen analytical techniques. These different methods have different strengths.

The method proposed by Andrews (1972) generates data relatively quickly, but these cannot be analysed graphically or statistically. Thus, significant, low amplitude variations are likely to be overlooked. The problems of representative sampling and investigator bias, which Andrews used to invalidate more quantitative approaches, apply equally to the relative abundance data, but Andrews argued that his approach avoids a false impression of precision.

A reliable model of sedimentation is required in Battarbee's (1973) technique. This can only be achieved by dating the sedimentary column at close intervals and is favoured in sites where there is a relatively constant rates of accumulation. Colinvaux (1978) doubted that such a model could be achieved in many sedimentary environments and suggested that large lakes and ocean basins are exceptions. When the rate can be modelled accurately, Battarbee's method solves most of the problems of data interpretation inherent in the relative method.

The relative method has the advantage that it provides data which can be expressed graphically and statistically, but the problem of discerning real changes from apparent changes in the frequency of individual species imposes an obvious interpretational constraint. Nevertheless, the data are more readily interpreted than those produced using Battarbee's method and an unrealistic sedimentation model.

The method selected for this investigation must enable salinity levels to be compared temporally and spatially. Andrews' (1972) approach is unsuitable because the data thus generated cannot be analysed statistically; an essential requirement if objective, replicable comparisons are to be made. As stated, it is only advantageous to use Battarbee's (1973) method if the rate of sedimentation can be calculated. At the sites investigated high organic content is restricted to a few strata and there have been many depositional environments and thus rates of deposition. This makes the generation of a reliable model of deposition very difficult, so the relative method is used with its inherent problems.

Andrews (1972) considered that bias introduced by the investigator is a major problem when attempting quantitative analysis. There are problems which result from the method of slide preparation and problems of replication because of the number of arbitrary decisions which must be taken. The latter problem can only be addressed if workers set out precisely what has been done and techniques must be carefully selected to reduce any such bias.

In the present investigation samples, 5 mm in thickness and approximately 125 mm^3, were taken at regular intervals from each core, the surface of which had been cleaned, and placed in plastic phials. The sediment was then allowed to stand overnight in a standard volume of 30% hydrogen peroxide. No heat was applied as this tends to fracture small diatom frustules (Shennan, pers. comm.). The phials were subsequently shaken and each one sampled using a new glass pippette. Two drops were placed on a 25 x 15 mm coverslip which was covered with distilled water and mixed using the pipette. The coverslip was heated very gently, so reducing the concentrating effect of evaporation (Battarbee, 1973), until the water had evaporated. The coverslip was then mounted using Microps and any excess Microps was removed with a scalpel.

Modern samples were collected from lagoons using the same type of plastic phials. A thumb was placed over the mouth of the phial which was then lowered to the surface of the bottom sediment. The thumb was removed momentarily, allowing sediment to enter, then replaced before the phial was brought to the surface and sealed with its plastic cap. Approximately 125

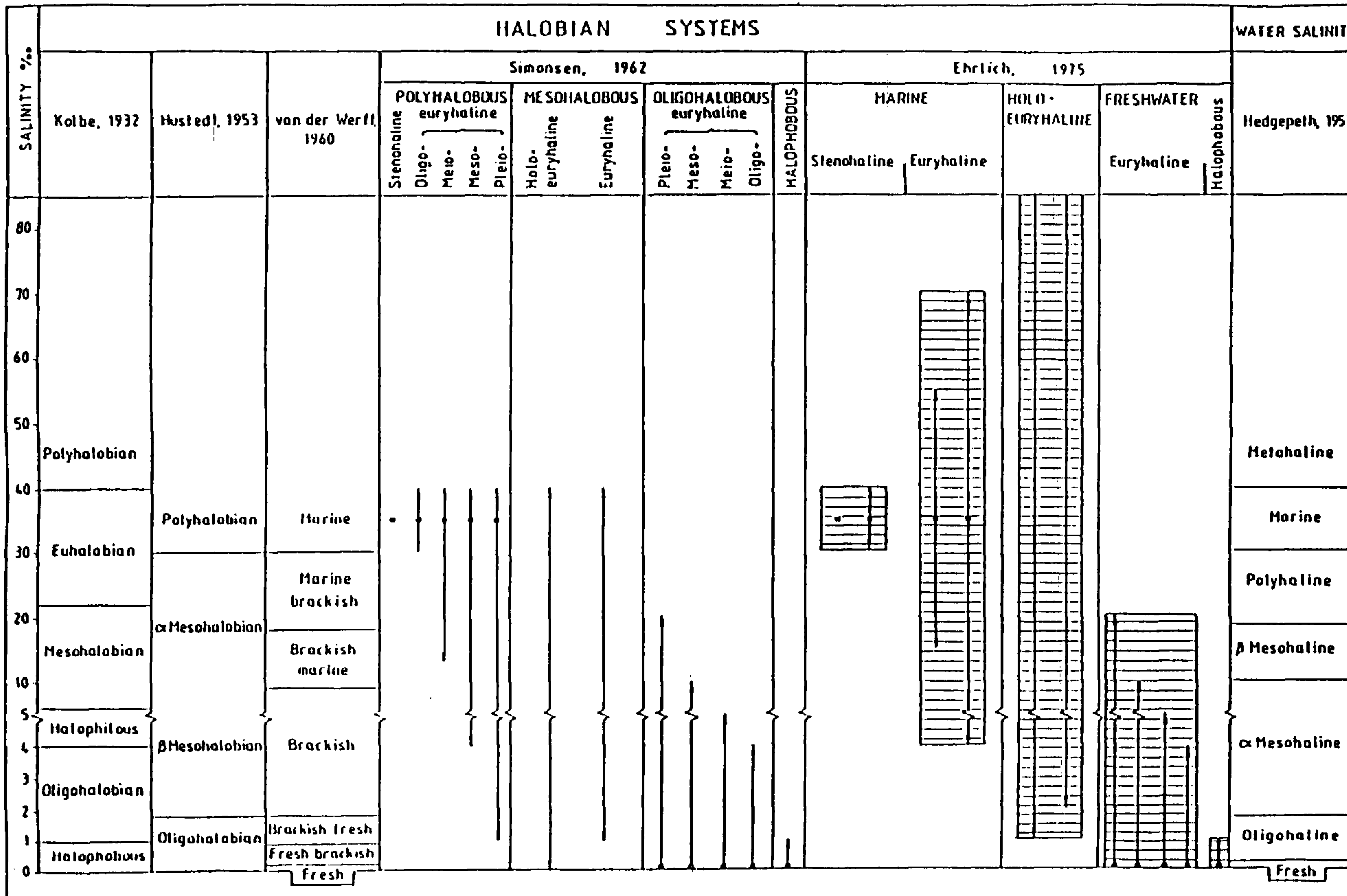
mm^3 of the bottom sediment was transferred to a new phial in the laboratory and the treatment described above was applied.

The diatoms on slides prepared in this way from sediments in the study area are readily observed. The loss of small diatoms from the sample (Andrews, 1972) is not a problem and mechanical damage is reduced to a minimum.

Whether diatom fragments should be counted is open to debate and is a problem which is often ignored, as Beyens and Denys (1982) pointed out. There are many situations in which diatoms may be expected to become fragmented, through predation, abrasion and/or compaction. Most marine diatoms, for example, pass through two digestive tracts before reaching the ocean bed, according to Cooper (1952). Furthermore, different genera will not be equally affected - large valves are more likely to break than small ones and elongated valves such as those of *Synedra tabulata* var. *grandis* (Mer.) Hust. are more likely to fracture than compact *Cocconeis pediculus* Ehr. valves. Equally, the siliceous framework of different valves varies in strength and certain parts of individual valves are more likely to survive.

Despite fragmentation, most broken valves are still identifiable, so, because certain species are almost never found as complete valves in these sediments, diatom fragments have been identified and counted. They were enumerated so that the possibility of a fragmented valve being counted more than once was eliminated. For Pennales, the central area was counted as one and the poles as half, these were totalled separately and whichever produced the greater sum was used. In practice the different genera tend to fall into one or other group because of identification requirements; in the case of *Eunotia* Ehr. species the poles were enumerated and in the case of *Navicula* Bory species the central area was counted. For Centrales, more than half a valve was required. This would obviously cause problems if the valve fractured in

Table 2.4 Halobian classification systems for diatoms (Adapted from Ehrlich, 1975 and Ireland, 1987)



many parts (Andrews, 1972), but experience indicates that, in the sedimentary environments under investigation, this is not a problem.

Valves were identified and enumerated using a Zeiss photomicroscope at 1575x and 2500x magnification. 200 valves, identified to at least species level, were counted at each level. Diatom determination was carried out to the finest possible level using the floras of Cleve-Euler (1951-1955) and Hustedt (1930, 1961) together with other floras, all of which are listed at Appendix I. Nomenclature generally follows Cleve-Euler (1951-1955).

The allocation of species and varieties to salinity groups is central to the use of diatom analysis in this study (Ireland, 1987). In any salinity regime the concentration of any species will vary spatially and with depth, but if the species are grouped according to salinity tolerance/preference these groups should be stable.

Field investigations have led to the production of several halobian classification systems (see Table 2.4).The differences partly reflect the different study areas; Hustedt's (1953) system was largely based upon his work on the River Weser, van der Werff (1960) worked in the nearby Eems-Dollard Estuary (Dutch-German Waddensea), Simonsen (1962) worked in the western Baltic and Ehrlich (1975) studied the Bardawil Lagoon (Northern Sinai). In addition, a few laboratory experiments, which utilize rate of photosynthesis and cell division rate as indicators of sensitivity to salinity-variations, have been carried out over wide salinity ranges. Unfortunately, very few species have been studied, for example Williams (1964) used 14 species and Admiraal (1977) examined only six. The experimental results do not contradict the field investigation, but suggest broader ranges of salinity tolerance than those proposed by Kolbe (1932), Hustedt (1953) and van der Werff (1960).

Table 2.5: A comparison of the salinity classification of several diatom species according to van der Werff (1960) and Ehrlich (1975)

(The species used in this table are found amongst the fossil assemblages examined in this study)

Werff (1960)	Ehrlich (1975)			
	Freshwater	Holoeuryhaline	Marine euryhaline	Marine stenohaline
FB	*Cocconeis placentula* Ehr. *Fragilaria pinnata* Ehr. *Gomphonema parvulum* (Kütz.) Grun. *Melosira granulata* (Ehr.) Ralfs *Pinnularia borealis* Ehr. *Surirella ovata* Kütz.			
BF	*Cyclotella meneghiniana* Kütz. *Navicula mutica* Kütz.	*Nitzschia sigma* (Kütz.) W.Sm.	*Nitzschia trybionella* Hantz.	
B		*Amphora coffaeiformis* Ag. *Mastogloia braunii* Grun. *Rhopalodia gibberula* (Ehr.) O. Müll.	*Achnanthes hauckiana* Grun. *Amphora holsatica* Hust. *Rhopalodia musculus* (Kütz.) O.Müll.	
BM			*Achnanthes brevipes* AG. *Nitzschia punctata* (*W.Sm.*) Grun. *Synedra tabulata* (Ag.) Kütz.	
MB			*Amphiprora alata* Kütz.	
M			*Amphora proteus* Greg. *Nitzschia granulata* Grun. *N. panduriformis* var. *minor* Grun.	*Coscinodiscus lineatus* Ehr. *Dimerogramma marinum* (Greg.) Ralfs *Navicula lyra* Ehr. *Paralia sulcata* (Ehr.) Cl.

The classifications of Simonsen (1962) and Ehrlich (1975) reflect both field investigation and theories developed largely as a consequence of laboratory experimentation. They remain, however, largely theoretical because only a small number of species has been classified according to these schemes. In constrast many diatoms have been classified according to the systems of Hustedt (1953) and van der Werff (1960) and unfortunately, as Table 2.5 illustrates, it is not simply a matter of redefining boundaries. *Amphora coffaeiformis* Ag. is classified as brackish according to van der Werff (1960) but as Ehrlich (1975) pointed out, it has been found in water with a salinity of less than 2‰ and in a hypersaline solar pond at 150‰.

Van der Werff's (1960) classification has not been as widely adopted as the Hustedt system (although the 1953 system has not been used consistently), but it is applied here for two reasons of comparability:

a) because van der Werff's (1960) classification further subdivides the Hustedt (1953) system it is possible to produce summary diagrams for both classifications. This is important because sea-level studies have employed both systems.

b) because Oliveira *et al.* (1955a,b) used the Hedgepeth (1953) classification for saline water in their study of the Maricá Lagoonal System and van der Werff's (1960) classification relates closely to this (see Table 2.4).

It is not possible, however, to ascribe diatoms classed as oligohalobian in the Hustedt (1953) classification, but not described by van der Werff and Huls (1958-66), precisely to the van der Werff (1960) system. In all cases they have been attributed to the least saline group.

Although the van der Werff (1960) system has been adopted there are two problems which should be borne in mind when interpreting the assemblages. Firstly, it is obviously not the ideal classification of diatom salinity tolerances, as illustrated by laboratory experiment. More work is required to permit the widespread adoption of a system similar to that of Ehrlich (1975). It should be noted, however, that Ehrlich's system and experimental work carried out by others have concentrated upon brackish water diatoms and that laboratory work needs to be carried out on the tolerances of freshwater diatoms. Nevertheless, it is possible to use the schemes of Simonsen (1962) and Ehrlich (1975) to aid interpretation when van der Werff's (1960) classification is used (Ireland, 1987).

Secondly, while distinct zones were found in the Eems Dollard Estuary by van der Werff (1960), it has not been shown categorically that this zonation is the result of the salinity gradient. Admiraal (1977) carried out laboratory experiments on six species taken from different parts of the same estuary and found that they had wide salinity tolerances. The distribution of two species may, however, be explained by their response to low salinities: *Navicula arenaria* Donk., which was collected from water with a mean salinity of about 30‰, showed retarded growth at 8‰, whereas *Nitzschia sigma* (Kütz.) W.Sm., which was growing in water with a mean salinity of about 10‰, grew well at 2‰. Nevertheless, Admiraal believed that other factors may govern diatom distribution in estuaries and quoted Bakker and de Pauw (1974) who suggested that turbulence is a major factor. If this is so, the classification may reflect salinity and turbulence, both of which are relevant to sea-level studies.

Diatom assemblages have often been subdivided according to benthic, epiphytic and planktonic forms (Miller, 1964; Shennan, 1980). This terminology has, however, not been used in a consistent way. The term epiphytic has not been restricted to species attached to plants, but used to describe forms fastened to a substratum (Miller, 1964).

Thus following Round (1981), the terms planktonic - free floating forms - and benthic - attached and bottom forms - are employed. Benthic includes both benthonic and epiphytic forms of Miller (1964) which eliminates the problem of classifying facultative epiphytes which are also bottom forms. The problem of classifying facultative planktonic species such as *Paralia sulcata* (Ehr.) Kütz. remains. These are classed as plankton because such valves are likely to be transported over greater distance in the water body than true benthic forms, thus not reflecting local conditions so precisely.

The diatom successions are zoned by salinity class - Local Diatom Salinity Phase (LDSP). Each phase is given the same abbreviation as the borehole, followed by a lower case letter, so It-1/33a is the first LDSP of borehole 33 at Lagoa de Itaipú Site 1. The numerical zonation methods of constrained single link analysis (CONSLINK), constrained divisive analysis using information content (SPLITINF), constrained divisive analysis using sum of squares deviation (SPLITLSQ) (Gordon and Birks, 1972) and principal components analysis (PCA) as described by Birks (1974) were used to aid zonation.

The diagrams were produced using a program written by Dr. I. Shennan of the University of Durham. Some modifications and the stratigraphic column were added by hand. Because of space limitations, genus names and, when necessary, species, variety and form names are abbreviated in a standard way as described in the species list (Appendix II).

2.5 Radiocarbon Dating

Samples for radiocarbon dating, the most common method of 'absolute' dating used in sea-level research, were all submitted to the radiocarbon laboratory of the Christian-Albrechts-Universität, Kiel, Federal Republic of Germany, where Professor Dr. H. Willkomm carried out age determinations using standard Kiel procedures in a gas proportional counter. As only one laboratory was used, inter-laboratory dating inconsistencies, highlighted by the International Study Group (1982), are avoided within the data set.

The cores from which material for radiocarbon dating was extracted were taken with the suction sampler, with the exception of the base of core It-1/33 which was sampled with a gouge. KI-2226.07 was taken from this section. Before material was removed for dating, the surface of the core which had been in contact with the sampling tube was removed and samples taken for diatom analysis and possible future pollen analysis. The latter were taken at 2.5 cm intervals and are currently stored in phials at 0° centigrade.

Most samples were submitted for dating before micropalaeontological analysis could be carried out, so were selected solely with reference to the lithostratigraphic record. Therefore, samples were generally taken at organic/inorganic boundaries, as such boundaries are most likely to have an indicative meaning. Following Tooley (1978), similar material was selected for dating whenever possible. This is predominantly well humified *Turfa herbacea.*

The sampled material was examined in petri dishes under x10 magnification and any pieces of wood and any visible roots or rootlets were removed. The weight of sample submitted followed the recommendations of Olsson (1979) and the resultant sample thickness reflects the diameter of the sampling tube. When ready for submission, the material was labelled and sealed in a polythene sleeve.

3. MODERN LAGOONAL DATA

3.1 Introduction

In this chapter environmental data derived from present-day lagoons in, or in the vicinity of, the study area will be presented and discussed. This study of the contemporary data aims to provide information to aid in the reconstruction of former depositional environments, and to ascertain whether it is appropriate to use some simple statistical techniques on diatom data derived from sediments. It comprises analysis of modern diatom death assemblages, consideration of bottom sediments and presentation of lagoonal tidal gauge records.

3.2 Analysis of modern diatom death assemblages

A diatom bioceonose is the assemblage of living diatoms which live and flourish in a given environment, under a particular combination of physical and biochemical factors. This relationship is exploited by micro-palaeontologists in an attempt to reconstruct former environments. The assemblage of frustular remains in a sedimentary unit, however, is one which accumulates at a particular site after death and before entombment. This diatom taphoceonose may represent the normal environment of the bioceonose, may result from the killing of the diatom population by a catastrophic change in one or more of the environmental factors, such as water salinity, or may represent valves and frustules transported into the site. In addition, diatoms from all three sources may be influenced by selective dissolution and by selective fragmentation of frustules (Jones, 1958; Reineck and Singh, 1980).

The problems of fragmentation have already been discussed in 2.4.1, but the problems of dissolution and displacement require further expansion.

Meriläinen (1973), in a review of the factors affecting the dissolution of diatom frustules, stated that in general, dissolution depends upon the following factors: the morphology of the water basin, the quality of the water, the silica content of the frustules, the quality of the frustules and the degree of biological interaction during the settling of diatoms. A deeper basin results in longer sinking times, thereby extending the time over which dissolution can occur. Water which is highly alkaline encourages dissolution (Jørgensen, 1955) as may a decreased hydrogen ion concentration in the water. Jørgensen (1955) suggested that upon death all the silica is dissolved from some species, so that they are always absent from deposits and Meriläinen (1973) illustrated this by describing how the thin-walled species *Attheya zachariasi* Brun is not found in the sediments of Lake Valkiajärvi even though it belongs to the plankton. Schrader (1971) described biological interaction between diatom frustules and planktonic herbivores, whereby frustules incorporated in the fecal pellets of planktonic herbivores are protected from dissolution by the pellet membrane.

Jones (1958) identified three types of microfossil displacement, all of which apply to diatom frustules. There is horizontal displacement (environmental mixing), vertical displacement from older to younger deposits (redeposition) and vertical displacement from younger to older depositis (stratigraphic leak). Environmental mixing and redeposition can be caused by many of the same processes. Streams and run-off transport freshwater taxa seaward and can erode older diatomaceous sediments. Tidal currents will carry marine and brackish taxa up into estuaries and may redeposit nearshore sediment further inland. Longshore currents and wave action cause environmental mixing and redeposition along coastlines and shores of large lagoons and lakes. Strong sea breezes can transport diatoms inland in spray droplets or erode and redeposit dry fossiliferous sediments. Water birds may take diatoms into their digestive systems or carry them on their plumage or feet, although the numbers are unlikely to be significant. Stratigraphic leakage, which is less common than environmental mixing or redeposition, can be caused by groundwater movement through coarse sediment, or by bioturbation through the action of burrowing animals such as crabs (Jones, 1958; Beyens and Denys, 1982).

In order to interpret fossil diatom taphoceenoses more accurately, it is necessary to study modern lagoonal death assemblages where the impact of a number of environmental factors can be assessed. To this end samples for diatom analysis were collected from the bottom sediments of Lagoa do Padre and Lagoa de Itaipú. No samples could be collected at Itaipu-Açu because there is now only an artificial channel, the Canal da Costa, at this location.

The lagoons sampled are similar in size, but belong to different lagoonal systems with different sized catchment areas (Table 3.1) and different salinity regimes; Lagoa de Itaipú is more saline than Lagoa do Padre because it has a direct opening to the ocean. The closest opening to Lagoa do Padre is at Ponta Negra, which is separated from Lagoa do Padre by the Canal de Ligação and Lagoa de Guarapina. Together these cover an area of 10.5 km^2.

Table 3.1: Hydrological characteristics of L. do Padre and L. de Itaipú

Characteristics	Lagoa do Padre	Lagoa de Itaipú
area of lagoon	1.2 km^2	1.5 km^2
area of system	40 km^2	5.6 km^2
catchment area	270 km^2	43 km2
streams entering lagoon	0	5
streams entering system	16	9

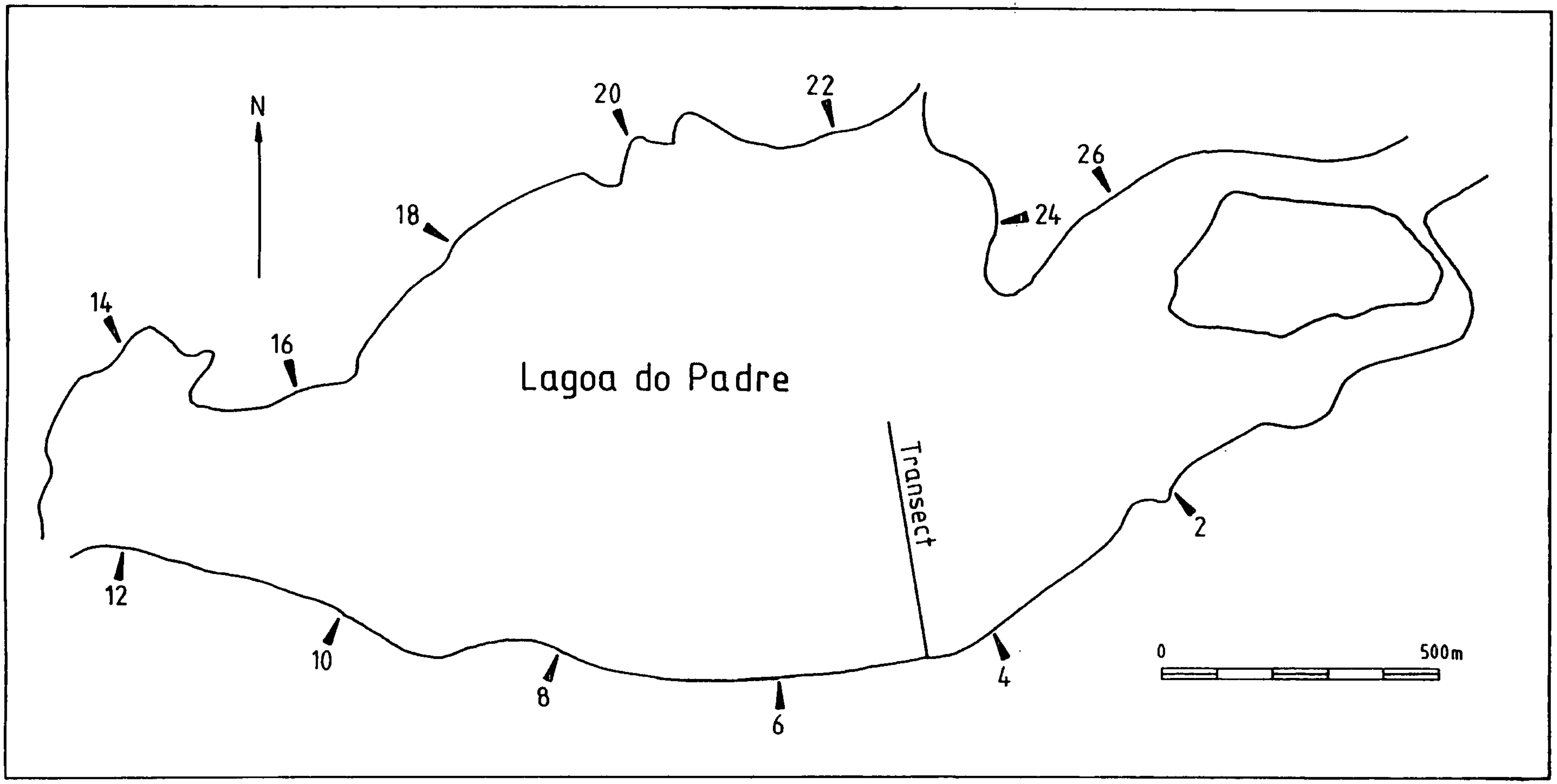


Figure 3.1 A map of Lagoa do Padre showing the location of bottom sediment sampling points

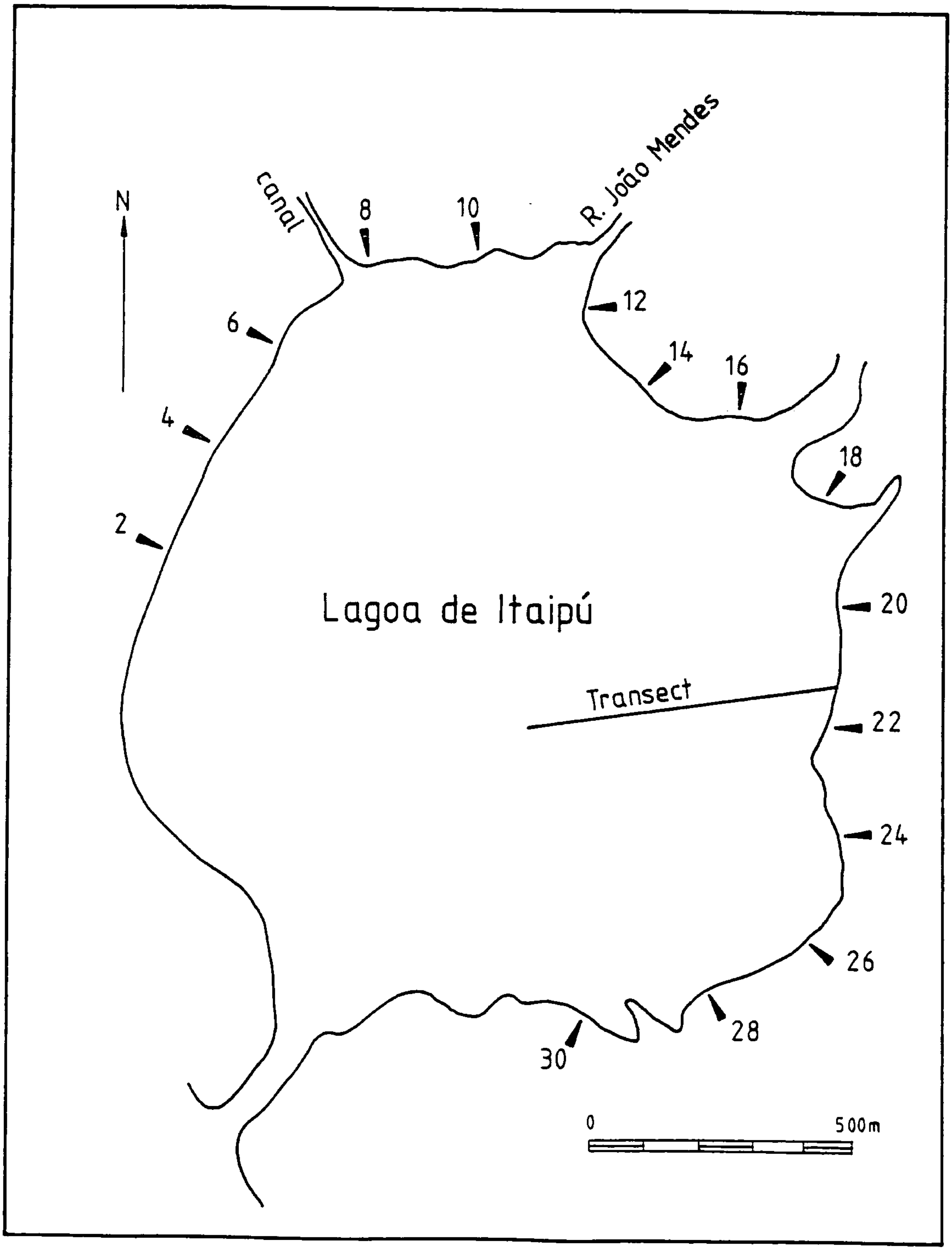


Figure 3.2 A map of Lagoa de Itaipú showing the location of bottom sediment sampling points

The sampling strategy was designed to test spatial variation and variation with depth of diatom death assemblages. Thus, at both lagoons, samples were taken along a 50 cm isobath and along a single transect of increasing water depth. Along the isobath samples were collected at 200 and 400 m intervals, at Lagoa de Itaipú and Lagoa do Padre respectively, and along the transect samples were taken at 5 cm depth intervals. The locations of the sampling points are shown in Figures 3.1 and 3.2.

3.2.1 Diatom salinity classification

As indicated in 2.4.1, the diatom salinity classification adopted here (van der Werff, 1960) does not reflect accurately the salinity tolerance of diatom species. It is possible to detect increasing and decreasing salinity, but it is not possible to be confident about the relationship between the classification and the salinity of the water body.

An attempt to measure the salinity of the water contained in the sample phials proved unsuccessful, presumably because chloride was concentrated in the bottom mud and increased the concentration in the water. The readings were all excessively saline. In 1955, however, Oliveira *et al.* (1955a,b) measured the salinity of water in various parts of the Maricá Lagoonal System. Salinities ranged from 6.7 to 8.4‰ with a reading of 8.4‰ in Lagoa do Padre. This is α mesohaline, following Hedgepeth (1953). Lagoa de Itaipú has been artificially opened since Oliveira (1948) studied the lagoon, so the salinity readings of 10‰ in the main body of the lagoon are no longer valid. Its present open nature plus the freshwater input of several streams and the canal from the closed Lagoa de Piratininga, should make the water ß mesohaline or polyhaline. Oliveira recorded a salinity of 22‰ on the lagoonward side of the *lido*.

According to the van der Werff (1960) classification, an ∝ mesohaline water body should be dominated by brackish diatoms, ß mesohaline by brackish-marine diatoms and polyhaline by marine-brackish diatoms (Table 2.4). But, as Table 3.2 illustrates the Lagoa do Padre assemblage is dominated by fresh-brackish diatoms which implies an oligohaline water body, and the Lagoa de Itaipú assemblage is dominated by brackish and brackish-fresh diatoms implying an oligohaline to ∝ mesohaline water body.

Table 3.2: Distribution of diatom valves by salinity class

a. Lagoa do Padre

Salinity class	F	FB	BF	B	BM	MB	M
mean (%)	16	55	10	14	1	1	3
standard deviation	8	14	9	7	1	1	2
minimum (%)	4	33	0	5	0	0	0
maximum (%)	32	78	32	29	3	2	8

b. Lagoa de Itaipú

Salinity class	F	FB	BF	B	BM	MB	M
mean (%)	1	10	22	40	11	3	13
standard deviation	2	15	10	13	10	2	6
minimum (%)	0	0	10	23	3	0	6
maximum (%)	9	50	47	64	36	7	27

If, however, rather than interpreting the van der Werff classification rigidly, the spread of salinity classes at each lagoon is examined, following Ehrlich (1975), a different picture emerges. At Lagoa do Padre 96% of valves are fresh or brackish which, according to Ehrlich is what would be expected in an

∝ mesohaline water body (Table 2.4). This is in agreement with the Oliveira *et al.* (1955a,b) salinity. At Lagoa de Itaipú there are fresh, brackish and marine diatoms present which according to Ehrlich would characterize a ß mesohaline water body. Here, however, the situation is complicated by the entry of the canal and the only sizeable stream, the Rio João Mendes, in the northwest of the lagoon. If the samples from this vicinity are separated from those elsewhere in the lagoon a more clear-cut picture emerges, as illustrated in Table 3.3. In the northwest of the lagoon 29% of the diatoms are freshwater and the assemblage suggests ß mesohaline water. Elsewhere 99% of the diatoms are brackish and marine which is characteristic of polyhaline water.

Table 3.3: Distribution of diatom valves by salinity class, divided according to the water characteristics of Lagoa de Itaipú

a. Samples 4-12 (adjacent to main sources of fresh water)

Salinity class	F	FB	BF	B	BM	MB	M
mean (%)	3	26	17	33	6	4	11
standard deviation	3	15	4	10	3	2	4
minimum (%)	0	9	12	23	3	1	6
maximum (%)	9	50	23	50	10	7	18

b. Samples 14-28

Salinity class	F	FB	BF	B	BM	MB	M
mean (%)	0	1	24	43	15	2	15
standard deviation	0	1	11	13	11	2	6
minimum (%)	0	0	10	29	3	0	8
maximum (%)	1	2	35	64	36	6	27

In such shallow lagoons (mean depth *c.* 0.5 m) water depth has no significant influence upon the salinity classification. This is illustrated in Figure 3.3.

It appears, based on this small sample, that the salinity of a water body can be established from a diatom assemblage classified according to van der Werff (1960) if the relative salinity tolerances of diatoms, as identified by Ehrlich (1975), are used to interpret the salinity data.

3.2.2 Species composition and salinity

The salinity of the water is markedly different in the two lagoons, yet the majority of species is common to both lagoons. There are 38 species found in both lagoons, making up 94% of the valves at Lagoa do Padre and 89% of the valves at Lagoa de Itaipú. Species which are found in only one lagoon always comprise less than 20%, and generally less than 5%, of any assemblage. This picture is to be expected because of the wide salinity tolerances of many species (Simonsen, 1962: Ehrlich, 1975). Nevertheless, 26% of species identified at Lagoa do Padre and 32% of those at Lagoa de Itaipú were not found in the other lagoon.

The 50 cm isobath assemblages at Lagoa do Padre are dominated by *Fragilaria pinnata* f. *subrotunda* May. and *Fragilaria brevistriata* Grun. (Figure 3.4). At Lagoa de Itaipú, the benthic assemblages are dominated by *Amphora coffaeiformis* var. *borealis* (Kütz.) Cl., *Mastagloia braunii* Grun. and *Nitzschia frustulum* (Kütz.) Grun. (Figure 3.5).

3.2.3 Species composition and water depth

Along the Lagoa de Itaipú transect, the species which dominate the 50 cm isobath assemblages are again dominant (Figure 3.6). At Lagoa do Padre, however, the relatively shallow water between 15 and 35 cm depth is dominated by *Navicula cincta* var. *typical* A.Cl., while that at 10 cm and

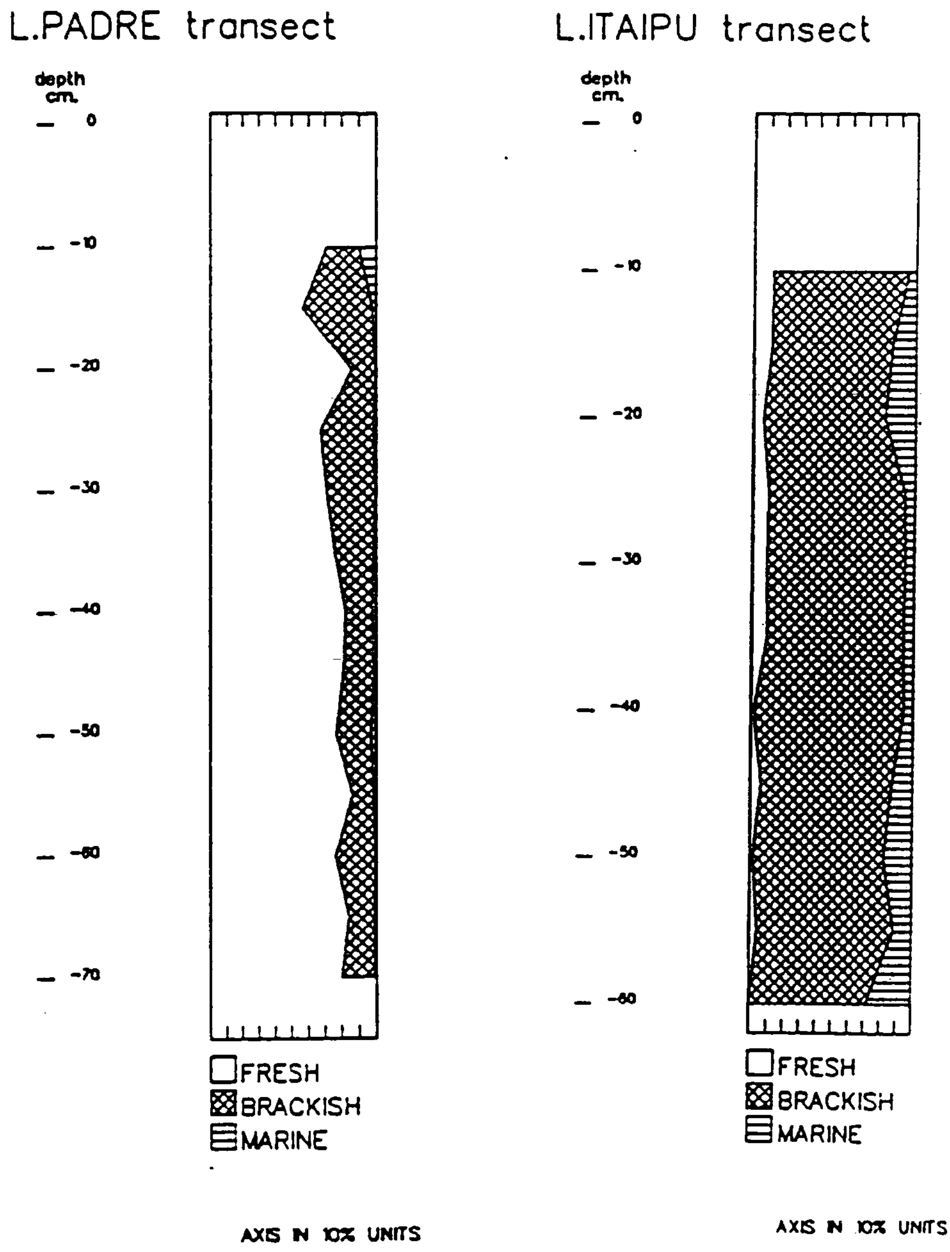


Figure 3.3 Summary diagrams showing the effect of water depth upon the distribution of diatom salinity groups in Lagoa do Padre and Lagoa de Itaipú

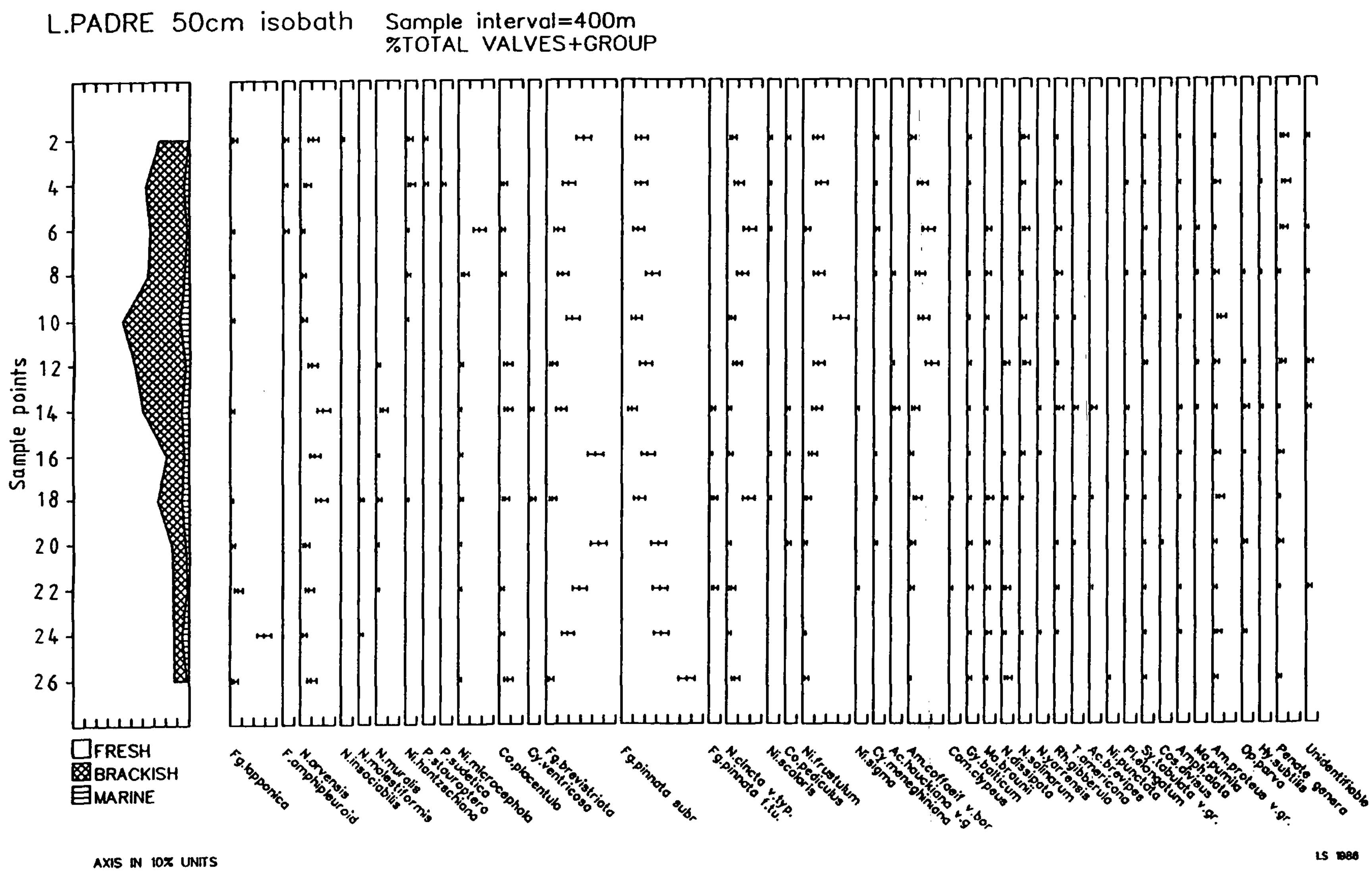


Figure 3.4 A diagram showing death assemblages along the 50 cm isobath at Lagoa do Padre

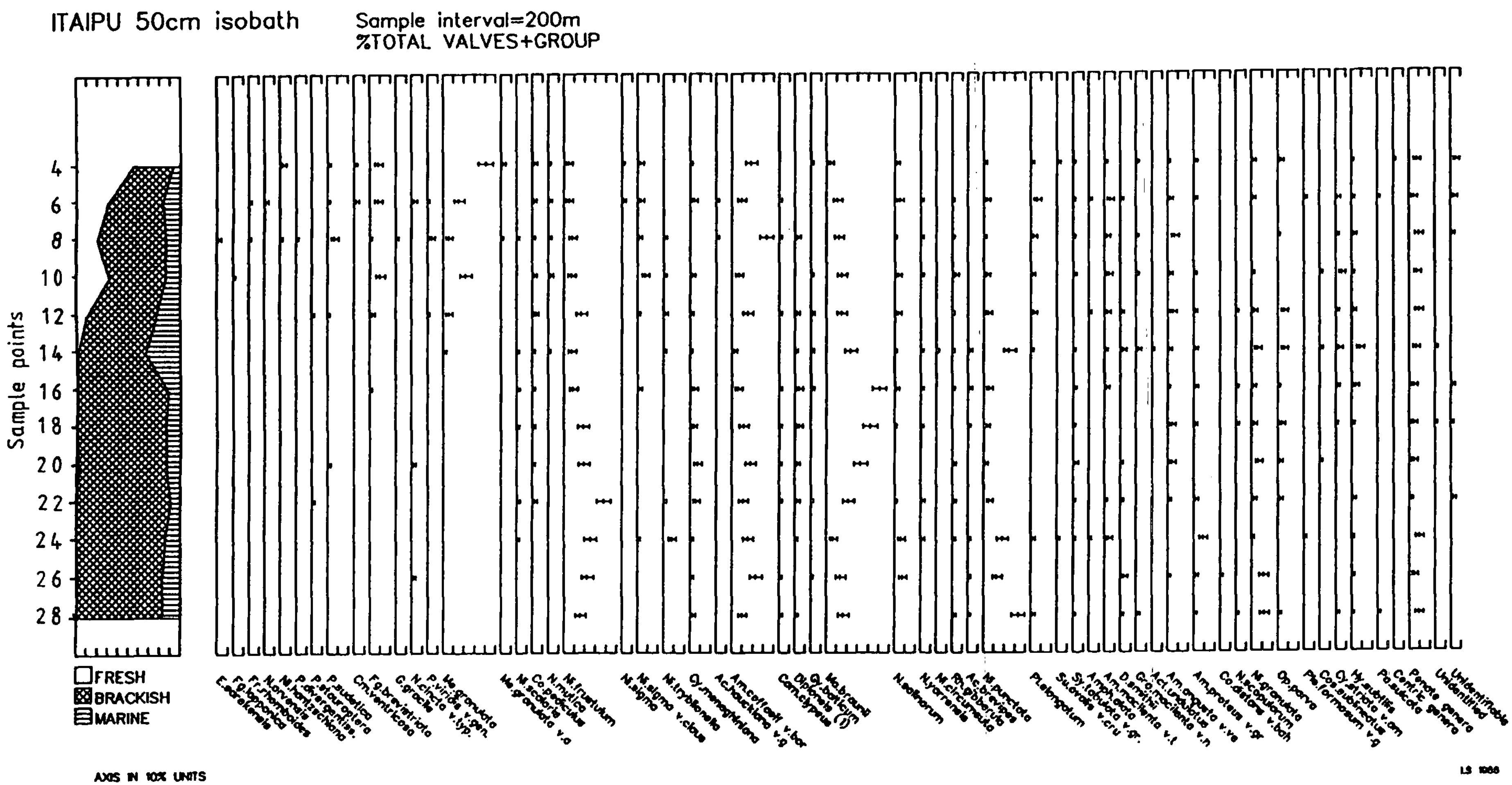


Figure 3.5 A diagram showing diatom death assemblages along the 50 cm isobath at Lagoa de Itaipú

between 35 and 70 cm depth is dominated by *Fragilaria pinnata* f. *subrotundra* May. and *Fragilaria brevistriata* Grun. (Figure 3.7).

Round (1981) stated that it is usually assumed that diatom deposition is relatively uniform over a lake bottom except where the sediments are disturbed by waves or are near inflows or outflows. This seems to hold true for Lagoa de Itaipú, but not Lagoa do Padre. Bradbury and Winter (1976) found variation along a transect of Lake Sallie, Minnesota, but their eight sampling points ranged between about 1 and 8 m depth, considerably deeper than in the present study. They did, however, refer to the work of Jørgensen (1948) in which the environmental preferences of the littoral diatom *Fragilaria* Lyn. are considered. During cell division they form long ribbons of individuals, which become loosely attached to convenient substrates. This makes shallow, highly agitated water unsuitable and quiet littoral water where currents and waves are slowed by aquatic macrophytes is preferred. In Denmark they are found in the deeper littoral areas of lakes and ponds. This seems, with the exception of the 10 cm sample, to hold true in Lagoa do Padre. Indeed, this factor could prove useful as an indicator of increasing or decreasing water depth and/or energy in freshwater environments.

3.2.4 The relative representation of planktonic forms and *Fragilaria*

In a study of the Littorina Transgression of western Skåne, South Sweden, Digerfeldt (1975a) found that changes in the relative representation of planktonic forms and *Fragilaria* Lyn. gave the most detailed indication, respectively, of periods of transgressive and regressive tendency. The relative representation of planktonic forms and benthic forms, excluding *Fragilaria* Lyn. was found to give an incomplete picture when compared with changes in the relative frequency of the hystrichosphaerid *Hystrichosphaeridium centrocarpum* which is a marine/brackish indicator.

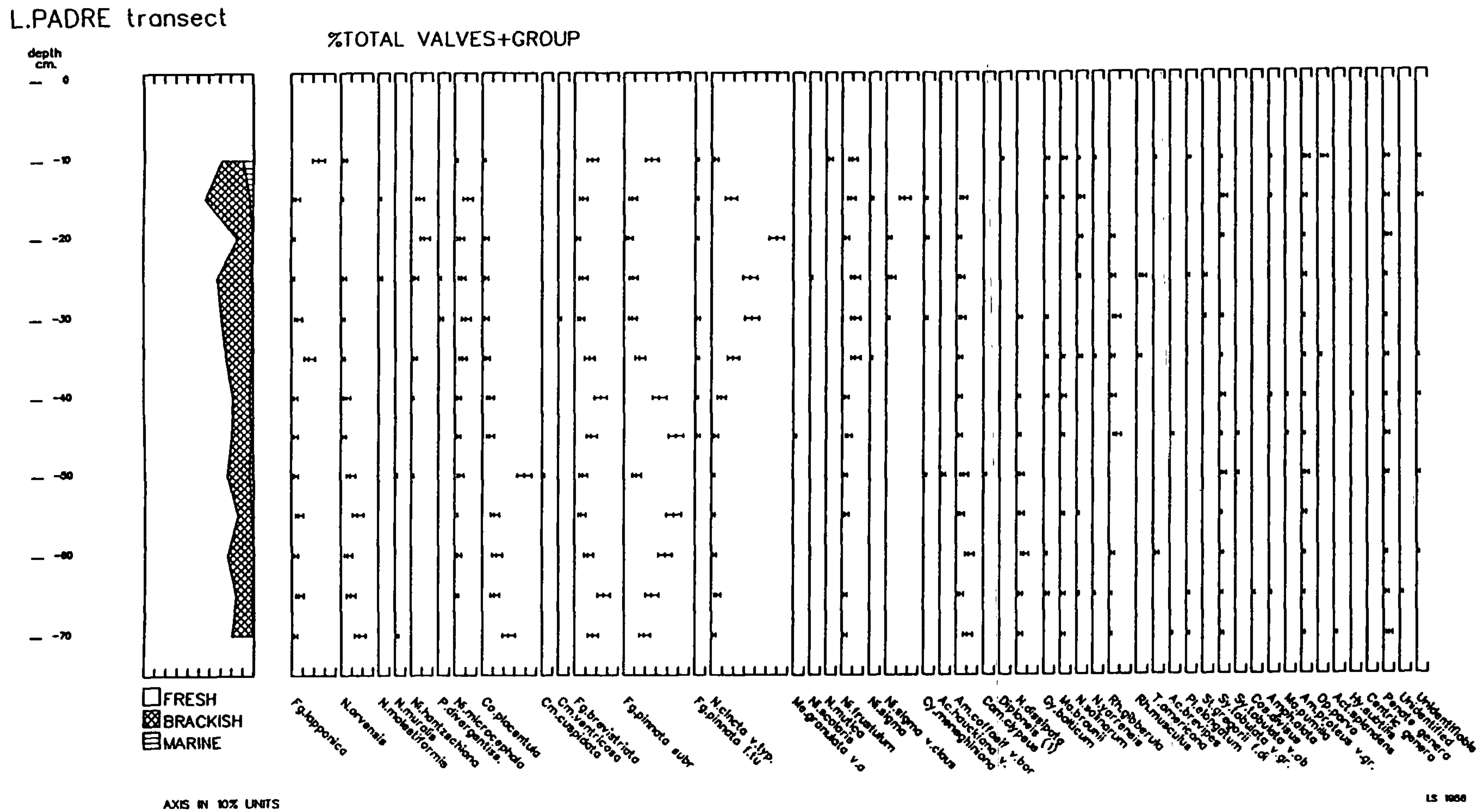


Figure 3.6 A diagram showing diatom death assemblages along a transect from 10 to 70 cm water depth at Lagoa do Padre

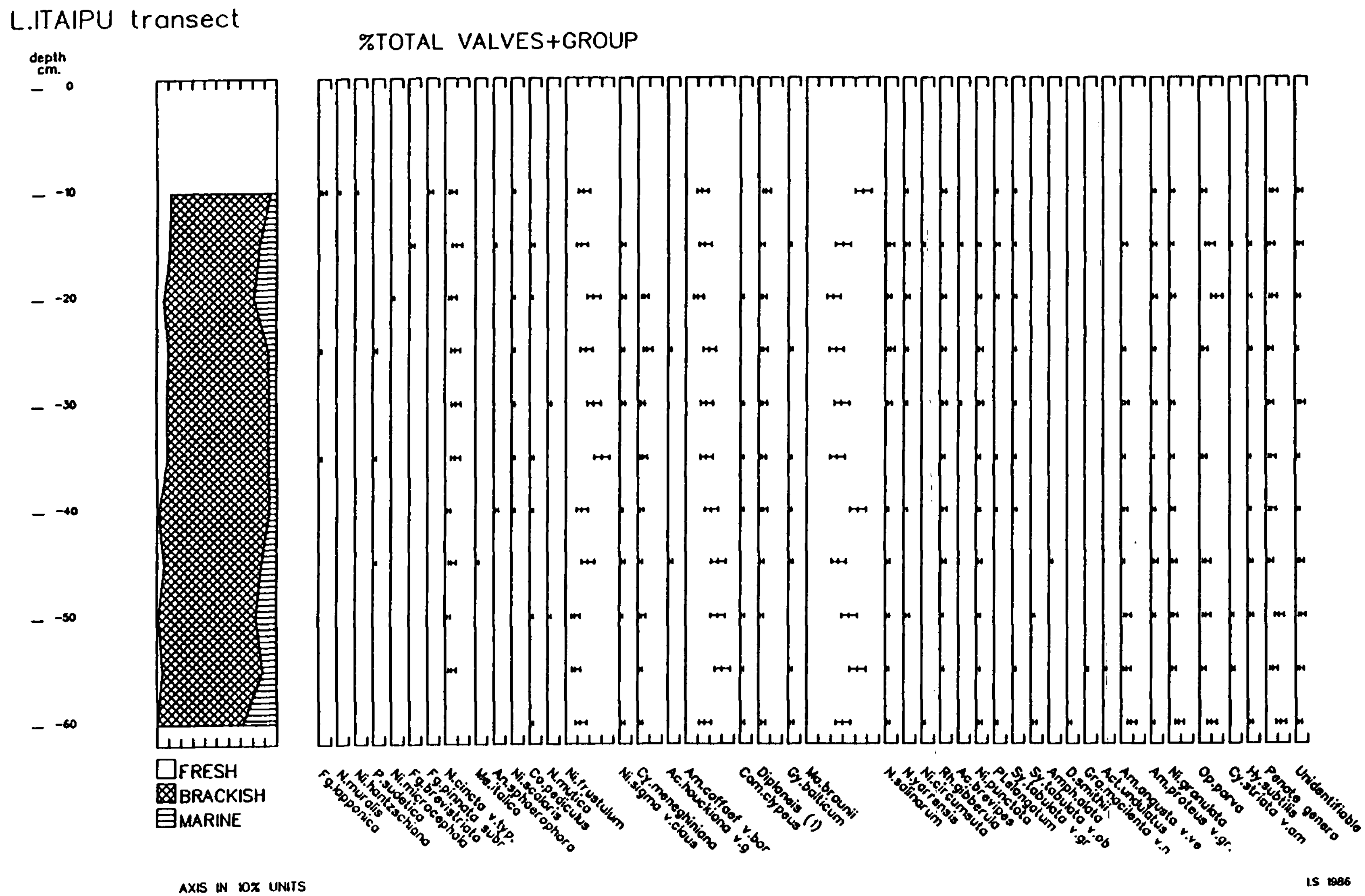


Figure 3.7 A diagram showing diatom death assemblages along a transect from 10 to 60 cm water depth at Lagoa de Itaipú

The frequencies of the latter were calculated with respect to the sum of arboreal pollen, so are independent of diatom frequencies.

Here, rather than comparing the planktonic - *Fragilaria* Lyn. representation with planktonic and non-planktonic forms, excluding *Fragilaria* Lyn., the former will be compared with the more normal benthic-planktonic representation. The benthos has been subdivided into the haptobenthos (attached to solid surfaces, either organic or inorganic) and the herpobenthos (moving in sediment) (Round, 1981).

The lack of further subdivision of the haptobenthos into epiphyton (growing on plants) epilithon (growing on rock surfaces) and epipsammon (growing on sand grains) reflects the influence of the work of Main and McIntire (1974) which indicates that few attached diatoms are frequently more abundant on host plants than on non-living substrates, while others are equally prominent in both epiphytic and epilithic floras.

If the planktonic - *Fragilaria* Lyn. representation is a meaningful indicator of regressive and transgressive tendencies, the *Fragilaria* Lyn. percentage should be greatest in the ∝ mesohaline water of Lagoa do Padre and lowest in the polyhaline water of Lagoa de Itaipú. Table 3.4 shows that this is indeed the case and indicates the *Fragilaria* Lyn. percentage that can be expected in ∝ mesohaline through to polyhaline water.

Table 3.4: Percentage of *Fragilaria* valves present in the diatom death assemblage recovered in waterbodies of different salinity

Waterbody	Mean %	Standard deviation	Minimum %	Maximum %
Lagoa do Padre (∝ mesohaline)	98.2	2.0	93	100
Lagoa de Itaipú (ß mesohaline)	18.6	7.7	5	26
Lagoa de Itaipú (polyhaline)	0.6	1.7	0	5

Along the Lagoa de Itaipú transect there is an inverse relationship between depth and *Fragilaria* Lyn. percentage. At 10cm depth there is 100% *Fragilaria* Lyn., at 15cm there is 50%, between 20 and 25cm there is a mean of 4% and between 40 and 60 cm there is 0%. This may reflect lifeform zonation similar to that described by Bradbury and Winter (1976) where *Fragilaria* Lyn. is littoral and planktonic diatoms dominate deep water. Nevertheless, irrespective of the cause, if this relationship is consistent it may be used as an indicator of transgressive and regressive tendencies in polyhaline water.

If the planktonic - *Fragilaria* Lyn. representation is compared with the haptobenthic - herpobenthic - planktonic representation of Figure 3.8, it is clear that the latter shows no consistent relationship with increasing salinity and in comparison does not offer a worth while indication of sea-level tendency. Thus, the former will be used when examining the fossil diatom evidence but the latter will not.

3.2.5 The problem of allochthonous valves.

In order to determine successfully the salinity of a water body from a diatom assemblage it is essential to consider only autochthonous valves. Beyens and Denys (1982) point out that diatoms may be transported vertically or laterally and in some cases such valves may exceed the number of *in situ* valves. This allochthonous component is, however, often difficult to recognize.

Simonsen (1969) suggested that benthic forms should be used to indicate the autochthonous component, as planktonic forms are more likely to be transported. By adopting this approach and plotting the percentage of benthic species against salinity class, a more accurate picture of the autochthonous

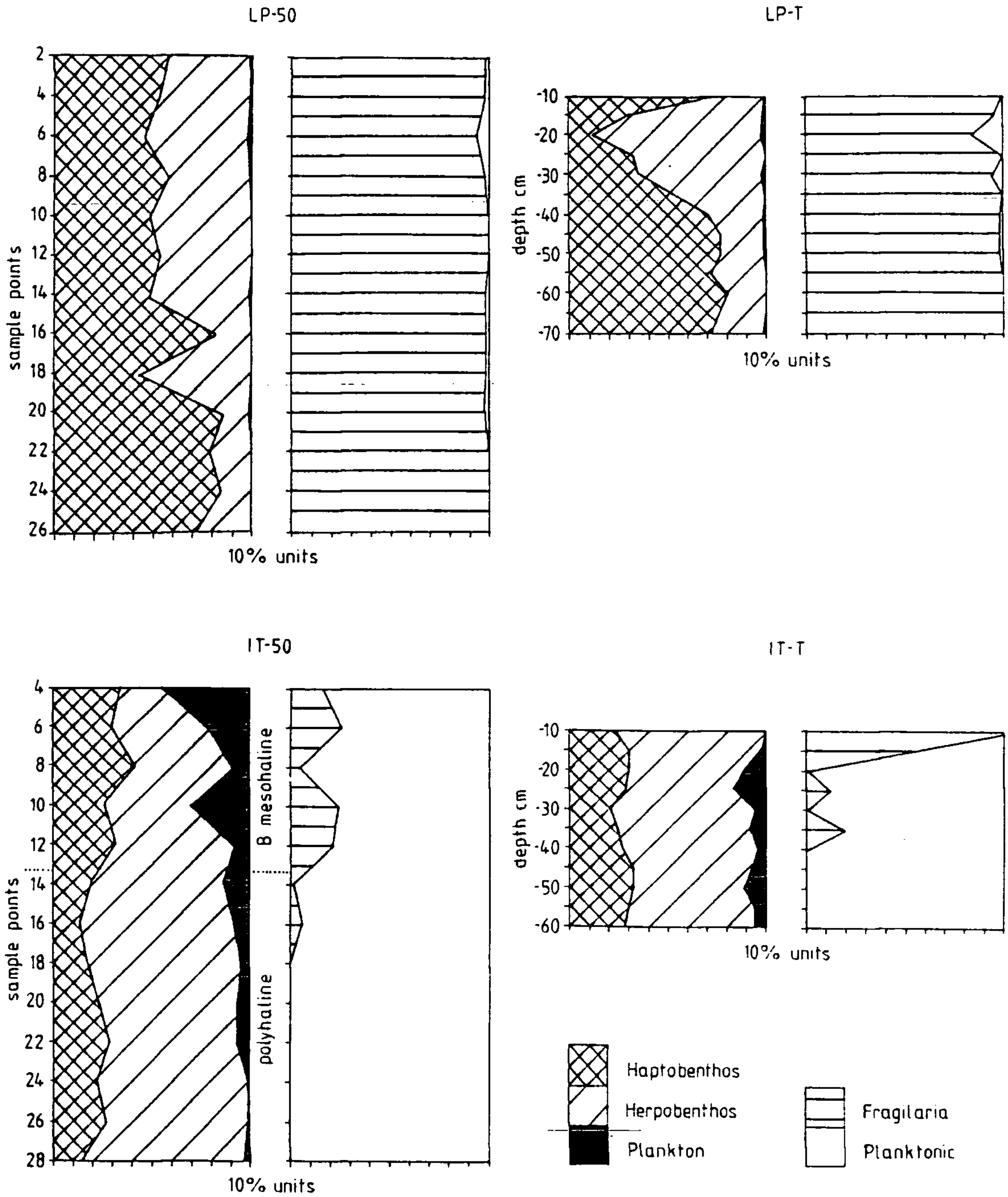


Figure 3.8 A comparison of the haptobenthic - herpobenthic - planktonic representation and the planktonic - *Fragilaria* representation for Lagoa do Padre (LP-50 and LP-T) and Lagoa de Itaipú (IT-50 and IT-T)

population should emerge, but the possibility that benthic forms may be transported is not addressed.

Beyens and Denys (1982) described a method which attempts to resolve this problem and to quantify the allochthonous component so that subsequent samples can be compared mutually. It uses salinity dependence and benthic life style. In this method the percentage of benthic diatoms in each van der Werff (1960) salinity class is calculated. The class with the highest percentage (optimal group) and the classes immediately adjacent to this class are taken to represent the autochthonous population. Those which fall on the fresh side of this group are the fresh allochthonous population and those on the marine side are the marine allochthonous population. These groups are expressed as a ratio of the autochthonous population and become F- and M- values respectively.

The following model calculation is used by Beyens and Denys (1982):

optimal group:	brackish	30%
neighbour groups:	brackish-fresh	15%
	brackish-marine	10%
		Σ55% - autochthonous component
freshwater allochthonous group:	fresh-brackish	5%
	fresh	1%
		Σ6% - F-value : 0.11
marine allochthonous group:	marine-brackish	20%
	marine	19%
		Σ39% - M-value : 0.71

This approach does not take into account the true nature of diatom salinity tolerance as described by Ehrlich (1975). In α mesohaline or polyhaline water, in particular, where brackish diatoms are dominant the distribution is likely to be skewed. It is likely to be skewed towards the fresh classes in the α mesohaline case and towards the marine classes in the polyhaline case. Therefore, in order to avoid spurious results, it is essential to examine the nature of the distribution before selecting the autochthonous component. Also, while this component will generally include three classes, it should be increased to four or reduced to two if this is supported by the distribution. The need for such modifications can be illustrated with two examples, the first is an assemblage from Lagoa de Itaipú and the second is from Lagoa do Padre, as shown in Table 3.5. In Lagoa do Padre relatively few allochthonous diatoms would be predicted because of the closed nature of the lagoon and lack of streams entering it. At Lagoa de Itaipú, on the other hand, a larger allochthonous population would be anticipated. Higher F-values would be expected in the northwest of the lagoon, where the canal and Rio João Mendes enter. An input of marine allochthonous values would be predicted throughout the lagoon, reflecting its tidal nature, with higher M-values in the less saline northwest.

All the contemporary data from both lagoons have been processed using the original Beyens and Denys (1982) method and adopting the modified approach. The results are presented graphically in Figure 3.9 and some of the data are summarized in Table 3.6. These show that the modified approach consistently produces results which, within a particular environment, are less variable and which accord more closely with the predicted values than those produced using the Beyens and Denys (1982) method.

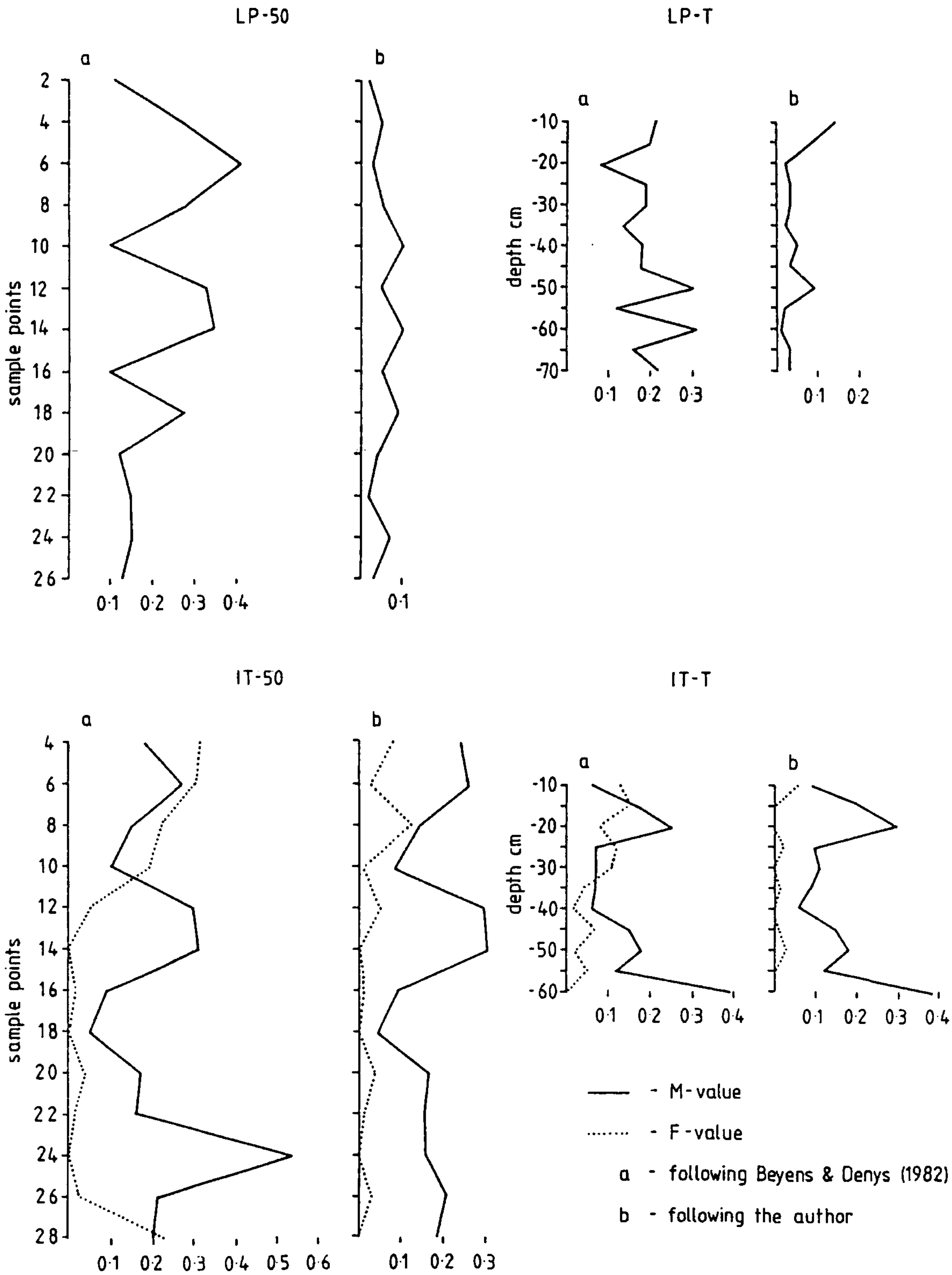


Figure 3.9 A comparison of F- and M- values for Lagoa do Padre (LP-50 and LP-T) and Lagoa de Itaipú (IT-50 and IT-T) produced (a) following Beyens and Denys (1982) and (b) following the author

Table 3.5: A comparison of the M-values resulting from (**A**) the Beyens and Denys (1982) method and (**B**) the modified Beyens and Denys method devised by the author.

Itaipú		**A**		**B**	
optimal group:	BF	34%	BF	34%	
neighbour groups:	FB	0%	B	31%	
	B	31%	BM	21%	
		Σ65%		Σ86%	
freshwater allochthonous group:	F	0%	F	0%	
			FB	0%	
		Σ0%		Σ0%	
marine allochthonous groups	BM	21%	MB	4%	
	MB	4%	M	10%	
	M	10%			
		Σ35%		Σ14%	
M-value		**0.69**		**0.16**	
Padre		**A**		**B**	
optimal group:	FB	33%	FB	33%	
neighbour groups:	F	28%	F	28%	
	BF	13%	BM	13%	
			B	17%	
		Σ74%		Σ91%	
marine allochthonous groups	B	17%	BM	3%	
	BM	3%	MB	2%	
	MB	2%	M	4%	
	M	4%			
		Σ26%		Σ9%	
M-value		**0.16**		**0.10**	

Table 3.6: Summary of the F- and M- values derived using the original Beyens and Denys (1982) method and the author's modified method for **(a)** α mesohaline water - Padre - **(b)** ß mesohaline water - NW Itaipú - and **(c)** polyhaline water - Itaipú excluding the NW.

	F-value		M-value	
	original method	modified method	original method	modified method
(a) mean			0.21	0.05
standard deviation			0.11	0.03
(b) mean	0.21	0.06	0.20	0.21
standard deviation	0.09	0.01	0.08	0.08
(c) mean	0.04	0.01	0.22	0.17
standard deviation	0.07	0.01	0.14	0.07

In the analysis of the fossil data, therefore, the modified method will be used, together with a summary diagram in which % benthic species is plotted against salinity class. In tandem these provide a very valuable aid to the identification of the autochthonous diatom assemblage. The allochthonous ratios should not be used in isolation because when an allochthonous salinity class becomes the optimal group, the resultant M- and/or F- values will be erroneous.

3.3 Consideration of modern lagoonal bottom sediments

A systematic sampling of lagoonal bottom sediments was not undertaken, but sediment which was recovered in the plastic phials during the collection of contemporary diatom samples gives a general impression of the nature of the bottom sediments in both lagoons. The small quantities of sediment may not be truly representative and were insufficient to permit particle size analysis.

In Lagoa de Itaipú, at a water depth of 50 cm, predominantly fine and medium grained, subrounded, quartz sand (Ga3, Gs1) is present up to 1 km to the east of the opening and 1.25 km to its west. Beyond this the bottom sediment comprises organic, silty clay (As2, Ag1, Sh1) as it does along the entire depth transect. This picture is essentially similar to the pattern observed by Muehe and Albuquerque (1976) in their study of the bathymetry and sedimentology of the lagoon (Figure 3.10), prior to its artificial opening. Although the present sedimentary environment favours coarser sedimentation in the southwestern part of the lagoon.

The sediment distribution in Lagoa do Padre is more variable than at Itaipú. Generally at a water depth of 50 cm the sediment is predominantly coarse grained, subrounded, quartz sand. Fine and medium grained quartz sand is present and in the northeast fine gravel forms up to 25% of the sediment. In several locations, however, the sediment is a highly organic clay. The depth profile can be divided into four zones: at 10 cm water depth there is predominantly coarse grained quartz sand; between 15 and 35 cm there is humified, herbaceous detritus; between 40 cm and 45 cm there is sandy, well humified, organic matter; between 50 and 70 cm there is predominantly coarse grained quartz sand.

At Lagoa do Padre the sediment variation with depth along the transect appears to have had a significant impact upon the diatom death assemblages, for there is precise agreement between the presence of sandy sediment and the dominance of *Fragilaria* Lyn.. *Navicula cincta* var. *typica* A.Cl. dominates where there is herbaceous detrital sediment. Indeed this is a stronger relationship than the one proposed in 3.2.1 following Jørgensen

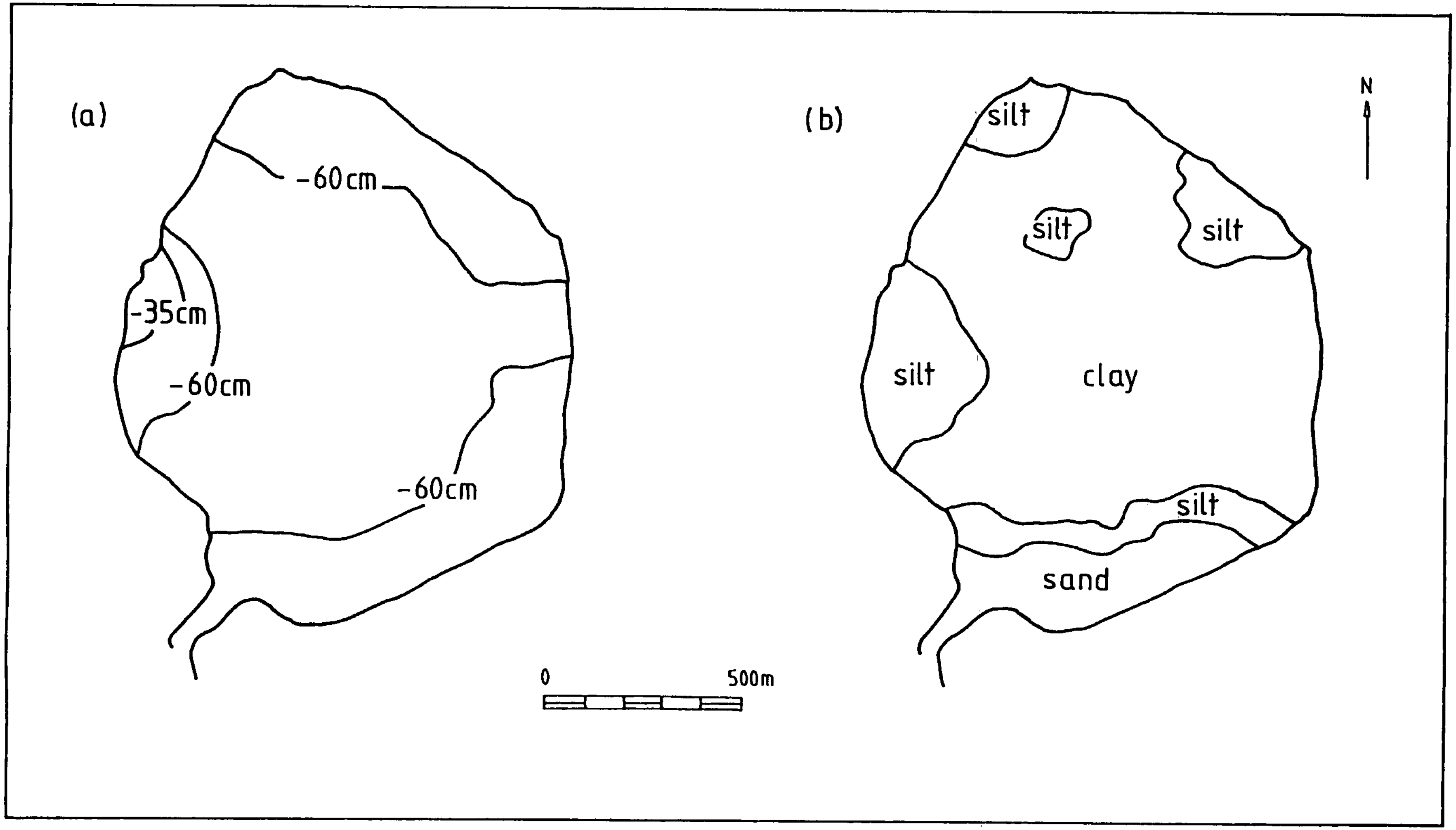


Figure 3.10 Maps showing (a) the bathymetry and (b) the sedimentology of Lagoa de Itaipú as determined by Muehe and Albuquerque (1976)

(1948). But, as Figure 3.6 illustrates, irrespective of the cause of the variation in % *Fragilaria* Lyn. along the Lagoa do Padre transect, as reflected in % haptobenthos, it does not influence the planktonic - *Fragilaria* Lyn. representation.

At Lagoa de Itaipú it is interesting to note that the sandy sediment analysed did not yield countable concentrations of diatoms.

3.4 The relationship between lagoon level and sea level

In order to relate ancient lagoon-level changes, as identified in the sedimentary and fossil evidence, to former sea-level changes the relationship between these levels must be established for both open and closed lagoons. Unfortunately, there are no naturally open lagoons along this coastline, only lagoons which have, relative to their size, very small artificial openings. Nevertheless, lagoons with single, narrow inlets and those lacking inlets present the greatest potential problem. If it can be established that the levels of closed and artificially opened lagoons have a relatively close relationship to MSL it can be assumed that lagoons with wide or numerous natural tidal inlets would have mean lagoon levels which relate more closely to MSL.

SERLA monitor lagoon levels in the study area using tide gauges. The data considered here were recorded continuously over a three year period (1980-1982), in five lagoons. Three of the lagoons, Lagoa de Maricá, Lagoa de Barra and Lagoa de Guarapina, are part of the Maricá Lagoonal System. Lagoa de Maricá is farthest from the artificial opening which connects Lagoa de Guarapina to the Atlantic, at Ponta Negra, through a 1.5 km long canal. The rock of the Ponta Negra headland was excavated to hydrographic zero (69 cm below MSL - Ilha Fiscal), but sand has subsequently built up in the channel (Oliveira *et al.*, 1955a,b). Tide gauge data suggest that this is now

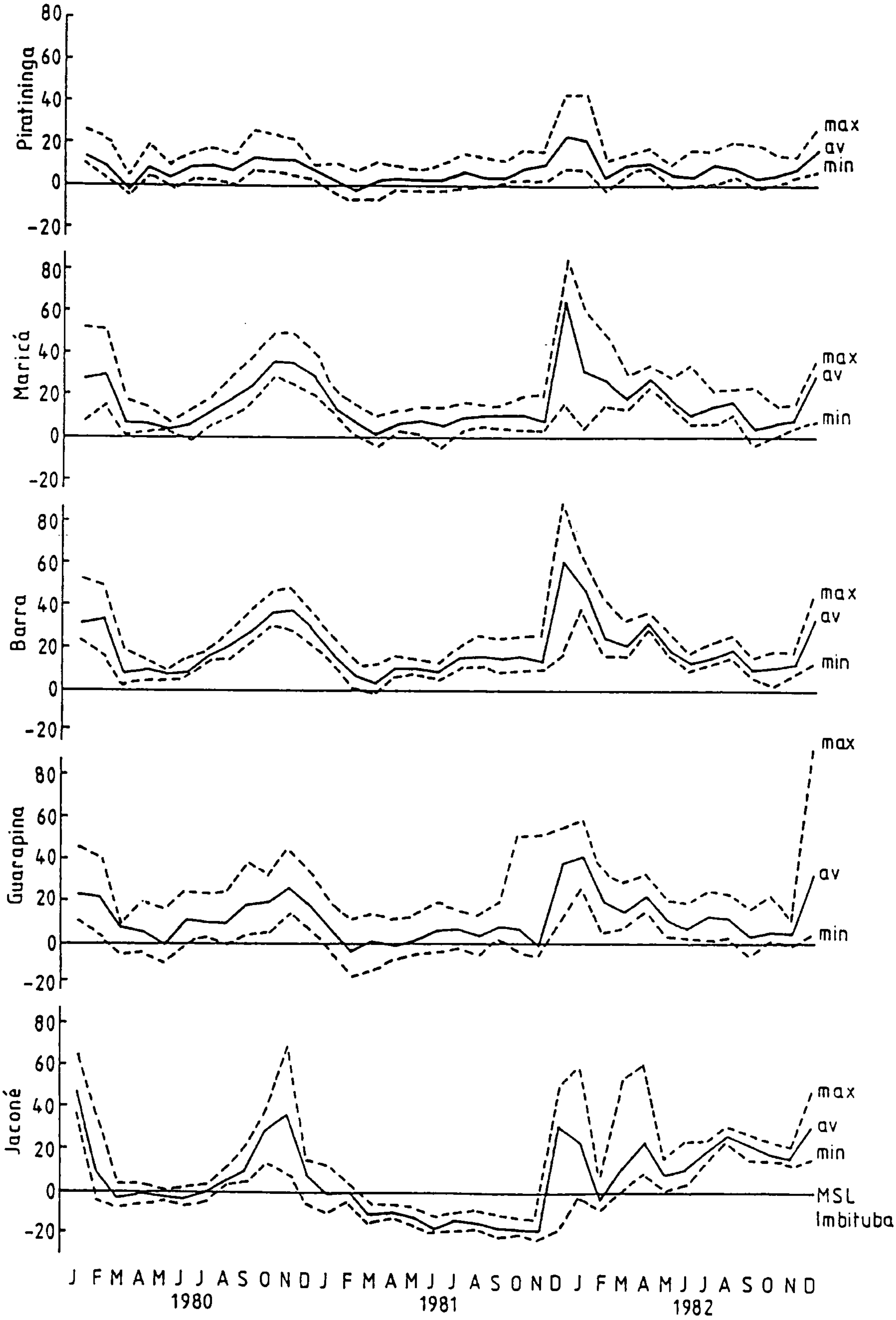


Figure 3.11 Graphs showing monthly lagoon-level variation between 1980 and 1982 in the Maricá Lagoonal System, Lagoa de Piratininga and Lagoa de Jaconé. (Water levels are shown in cm and zero = MSL-Imbituba)

75 cm above hydrographic zero, or 6 cm above MSL - Ilha Fiscal. The other two lagoons are Jaconé and Piratininga. Lagoa de Jaconé is a closed lagoon lying east of Ponta Negra. It is separated from the Atlantic by a barrier, but has an outflow in the form of a stream, the Sangado, which enters the closed Saquarema Lagoonal System. Lagoa de Piratininga is connected to Lagoa de Itaipú by a canal and, as described earlier, Lagoa de Itaipú is open to the ocean. Here the opening through the barrier is excavated to below hydrographic zero.

Along this coastline the diurnal tidal variation, which is generally less than 1.4 m, has little impact on the water level in those lagoons with tide gauges. The water level of Lagoa de Itaipú, however, does fluctuate in accordance with the tide. In the lagoons with gauges variation during the day is of the order of 2 cm. The most significant lagoon level variation in these relatively closed lagoons occurs on an annual rather than a daily cycle. It is relatively constant for most of the year, but rises in the wet season between November and April. As Figure 3.11 illustrates, this annual variation follows a similar pattern in all lagoons.

The relationship between lagoon levels and MSL is illustrated in Figure 3.12. The mean lagoon level for all lagoons is 36 cm above MSL - Ilha Fiscal that is approximately midway between MSL - Ilha Fiscal and mean high water spring (MHWS). The standard deviation is only 5 cm. The average monthly maxima and minima fall close to the mean lagoon level, but the three year, maximum ranges deviate more widely from the mean. The three year maxima deviate most from mean lagoon levels, with all five exceeding MHWS - Ilha Fiscal. On average, however, this level is only exceeded for 20 days per year and the mean three year maximum range of 85 cm is less than the tidal range. It is interesting to note here that historical studies, by Oliveira (1948) and Oliveira *et al.* (1955a,b), suggest that the low points, or

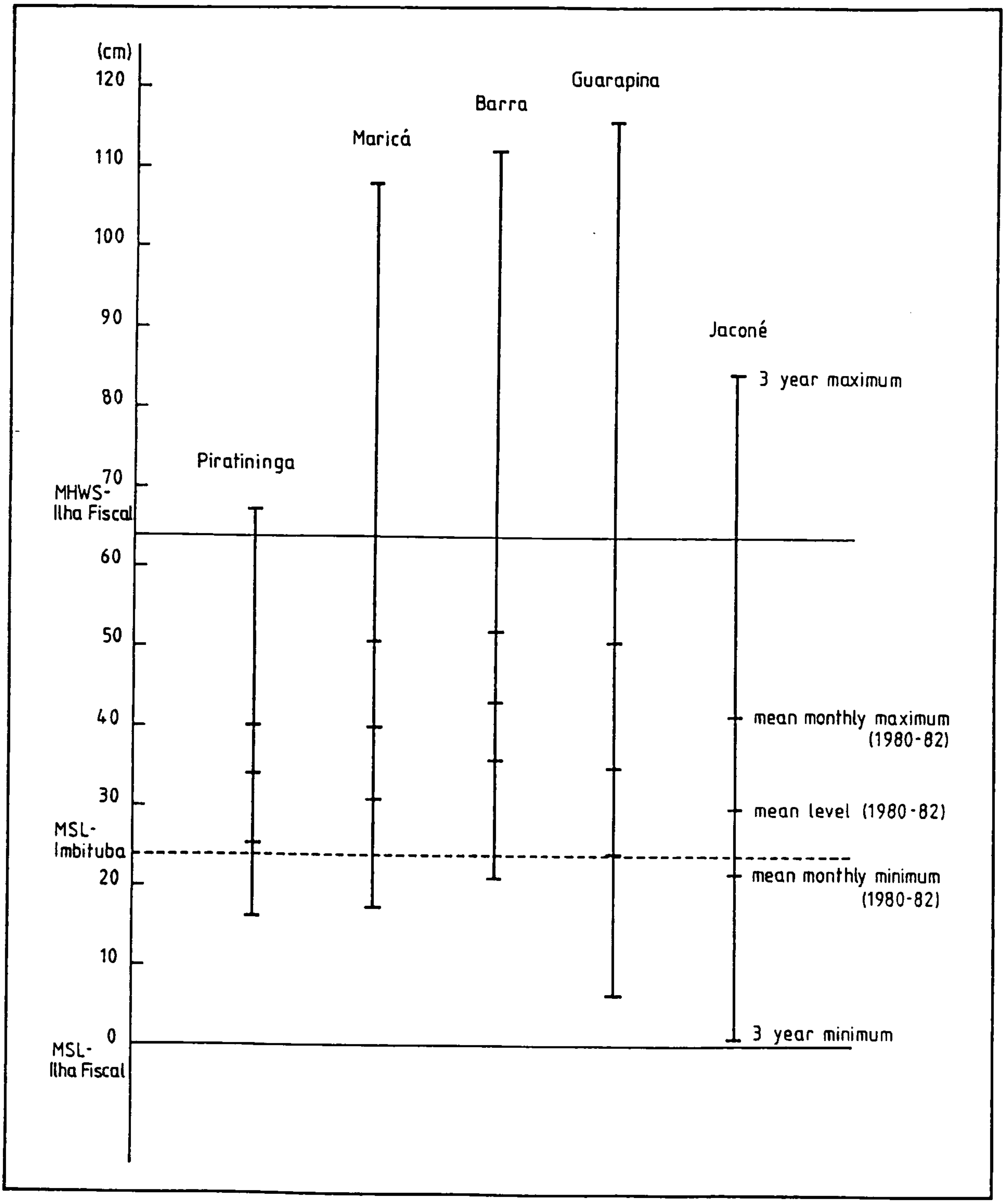


Figure 3.12 A diagram illustrating the relationship between lagoon levels in the study area and MSL-Imbituba, MSL-Ilha Fiscal and MHWS-Ilha Fiscal

lidos, of the barriers enclosing closed lagoons were lower than the level of the highest local tides. Many of these *lidos* have subsequently been built up artificially to allow road construction along the barriers.

A comparison of the lagoon level data of individual lagoons shown in Figure 3.12 suggests that the proximity to a small inlet may be less important in determining levels than the size of the catchment area. The three lagoons in the Maricá Lagoonal System - which has the largest catchment area - have similar 3 year maxima which are marked higher than those of Lagoa de Jaconé or Lagoa de Piratininga. This relationship should only hold true in relatively closed lagoons.

The evidence presented here indicates that mean lagoon level has a relatively constant relationship to MSL. Thus, even in closed lagoons the difference between the two levels is not significant within the accuracy limits of the methodology (see 2.2.1). In addition, the relationships presented in Figure 3.12 will enable more precise interpretations of former sea levels to be made from lagoonal sedimentary evidence.

4. SEDIMENTARY HISTORY

4.1 Introduction

In this chapter data obtained through the analysis of sedimentary sequences, predominantly sampled around present-day lagoons, will be described and interpreted. The sedimentary sequences at three study locations (Lagoa do Padre, Itaipu-Açu and Lagoa de Itaipú), each comprising two sites, were analysed using the techniques described in Chapter 2. In addition, stratigraphic analysis was carried out at Lagoa de Guaratiba. Radiocarbon age determinations will be presented separately, then, by locale, the results will be described and the sedimentary history interpreted. Most of the sites to be considered were discussed briefly by Ireland (1987).

4.2 Radiocarbon age determination

The radiocarbon dates are presented in Table 4.1. The Libby half life of 5568 years is applied and AD 1950 taken as zero BP. Dates are corrected to $\delta^{13}C = -25$ and the quoted error of $\pm$ 1σ is based solely on the counting statistics.

When the measured radioactivity is low relative to its error (as in KI-2226.05, KI-2226.07 and KI-2376.02) only a minimum age (T min) can be assumed. In these cases the age is calculated from $q + 1.65\sigma q$, where q is the ^{14}C content, so the probability that the sample is younger than T min is less than 5%. From the stand point of the radiocarbon dating method this in no way implies that the actual age lies in this region, but the probability that they are older than 80,000 BP is only 3% according to the measurements made in Kiel.

There appears to be an age reversal between KI-2226.06 and .07 because the T min of KI-2226.07 (38200 BP) was calculated using $q + 1.65\sigma q$. If the same

Table 4.1: Radiocarbon dates

No.	Site/Borehole	Coordinates	Material	Sample Thickness (cm)	Altitude (top of sample) (m)	Laboratory code	^{14}C Age ± 1σBP (BP = before 1950)	$\delta^{13}C$‰
1	Lagoa do Padre 1/32	22°57'03"S 42°45'22"W	herbaceous peat	8	-2.39	KI-2222.01	6800±110	-27.27
2	Lagoa do Padre 1/32	22°57'03"S 42°45'22"W	herbaceous peat	9	-2.61	KI-2222.02	7150±120	-27.93
3	Lagoa do Padre 2/12	22°56'34"S 42°46'54"W	herbaceous peat	8	1.42	KI-2223.01	2270±55	-28.82
4	Lagoa do Padre 2/12	22°56'34"S 42°46'54"W	herbaceous peat	9	1.04	KI-2223.02	2590±65	-28.07
5	Lagoa do Padre 2/12	22°56'34"S 42°46'54"W	fine detrital mud with clay	6	0.39	KI-2373.01	4850±80	-21.90
6	Lagoa do Padre 2/12	22°56'34"S 42°46'54"W	fine detrital mud with clay	8	0.04	KI-2373.02	5230±90	-22.40
7	Itaipu-Açu 1/3	22°57'48"S 42°54'20"W	herbaceous peat	8	4.9	KI-2224	250±48	-27.96
8	Itaipu-Açu 2/12	22°57'01"S 42°54'44"W	herbaceous peat	7	0.47	KI-2225.01	2460±55	-27.96
9	Itaipu-Açu 2/12	22°57'01"S 42°54'44"W	herbaceous peat	7	0.37	KI-2225.02	2700±60	-27.00
10	Itaipú.1/33	22°57'31"S 43°02'07"W	herbaceous peat	10	0.15	KI-2226.01	370±55	-25.38

No.	Site/Borehole	Coordinates	Material	Sample Thickness (cm)	Altitude (top of sample) (m)	Laboratory code	^{14}C Age ± 1σBP (BP = before 1950)	$\delta^{13}C$‰
11	Itaipú 1/33	22°57'31"S 43°02'07"W	herbaceous peat	9	-1.51	KI-2226.02	7110±110	-25.94
12	Itaipú 1/33	22°57'31"S 43°02'07"W	herbaceous peat	8	-1.73	KI-2226.03	7810±75	-24.31
13	Itaipú 1/33	22°57'31"S 43°02'07"W	herbaceous peat	7	-3.51	KI-2226.04	35300+3400 -2400	-27.25
14	Itaipú 1/33	22°57'31"S 43°02'07"W	herbaceous peat	6	-4.08	KI-2226.05	T min = 35400	-27.03
15	Itaipú 1/33	22°57'31"S 43°02'07"W	herbaceous peat	5	-4.34	KI-2226.06	42500+6000 -3400	-27.79
16	Itaipú 1/33	22°57'31"S 43°02'07"W	herbaceous peat	17	-5.44	KI-2226.07	T min = 38200	-24.90
17	Itaipú 1/34	22°57'30"S 43°02'06"W	herbaceous peat	8	-1.30	KI-2376.01	6860±110	-23.30
18	Itaipú 1/34	22°57'30"S 43°02'07"W	herbaceous peat	6	-4.13	KI-2376.02	T min = 36000	-28.50
19	Itaipú 2/25	22°57'27"S 43°02'57"W	herbaceous peat	8	-1.64	KI-2374.01	7140±110	-28.50
20	Itaipú 2/25	22°57'27"S 43°02'57"W	herbaceous peat	8	-2.07	KI-2374.02	8850±110	-27.00
21	Itaipú 2/25	22°57'27"S 43°02'57"W	herbaceous peat	8	-3.45	KI-2374.03	33300+1900 -1500	-27.60

No.	Site/Borehole	Coordinates	Material	Sample Thickness (cm)	Altitude (top of sample) (m)	Laboratory code	^{14}C Age $\pm 1\sigma$BP (BP = before 1950)	$\delta^{13}C$‰
22	Itaipú 2/26	22°57'30"S 43°02'58"W	herbaceous peat	8	-1.94	KI-2375.01	6840±100	-28.80
23	Itaipú 2/26	22°57'30"S 43°02'58"W	herbaceous peat	8	-2.31	KI-2375.02	7970±100	-27.80
24	Itaipú 2/26	22°57'30"S 43°02'58"W	herbaceous peat	10	-3.48	KI-2375.03	30500+1500 -1200	-29.00
25	Itaipú 2/26	22°57'30"S 43°02'58"W	herbaceous peat	9	-4.23	KI-2375.04	31200+2500 -1900	-25.00

level of confidence is also applied to K1-2226.06 its age limits become 37500 to 58700 BP.

Willkomm (pers. comm.) considering variations in the $^{14}C/^{12}C$ ratio and dendrochronological corrections, placed KI-2224 between AD 1500 and 1800 and KI-2226.01 between AD 1410 and 1650 (Pearson *et al.*, 1983). Samples from 2200 to 2700 BP (KI-2223.01,.02 and KI-2225.01,.02) will be 40 to 130 sidereal years older respectively (Pearson and Baillie, 1983) and samples from *c.* 7000 BP (KI-2222.01,.02, KI-2226.02,.03, KI-2376.01, KI-2374.01 and KI-2375.01,.02) will be 800 sidereal years older (Klien *et al.*, 1982).

4.3 Lagoa do Padre

Lagoa do Padre is a relatively small, shallow lagoon backed by a series of headlands and bays (Figure 4.1). The headlands are composed of red, highly weathered basement and the bays are filled with sediment. Tree-covered cliffs front the headlands which generally rise to about 25 m. In neighbouring lagoons, such as Lagoa de Guaratiba, the cliffs are more frequently vertical and unvegetated. Embayments have cut back from both Lagoa do Padre and Lagoa de Guaratiba, joining to form low cols between the headlands, but exploratory borings indicate that the lagoons have never been joined across the cols. Sand barriers now separate many of the bays from the lagoon.

The *restinga* which separates the lagoon from the Atlantic was identified by Muehe (1982), using aerial photography, as a single barrier. Field investigation, however, revealed that it has formed from the merging of two once distinct barriers. The older, higher barrier is only preserved at the eastern end of the lagoon, where it is separated from the younger, complete barrier by a linear depression. This has now been partially filled to facilitate road building on the barrier, an activity which has destroyed much of the

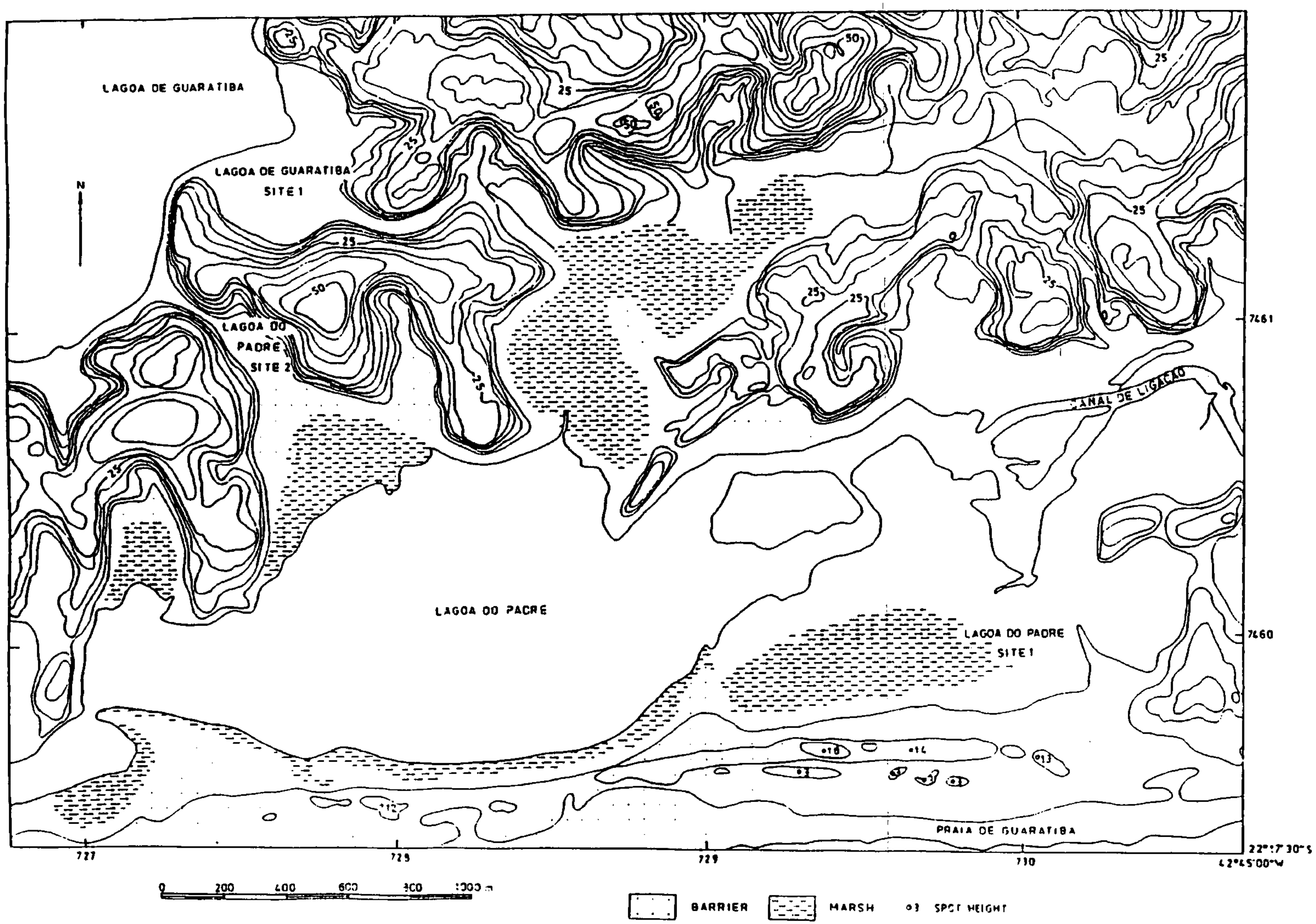


Figure 4.1 A map of Lagoa do Padre and part of Lagoa de Guaratiba, showing the location of sampling sites

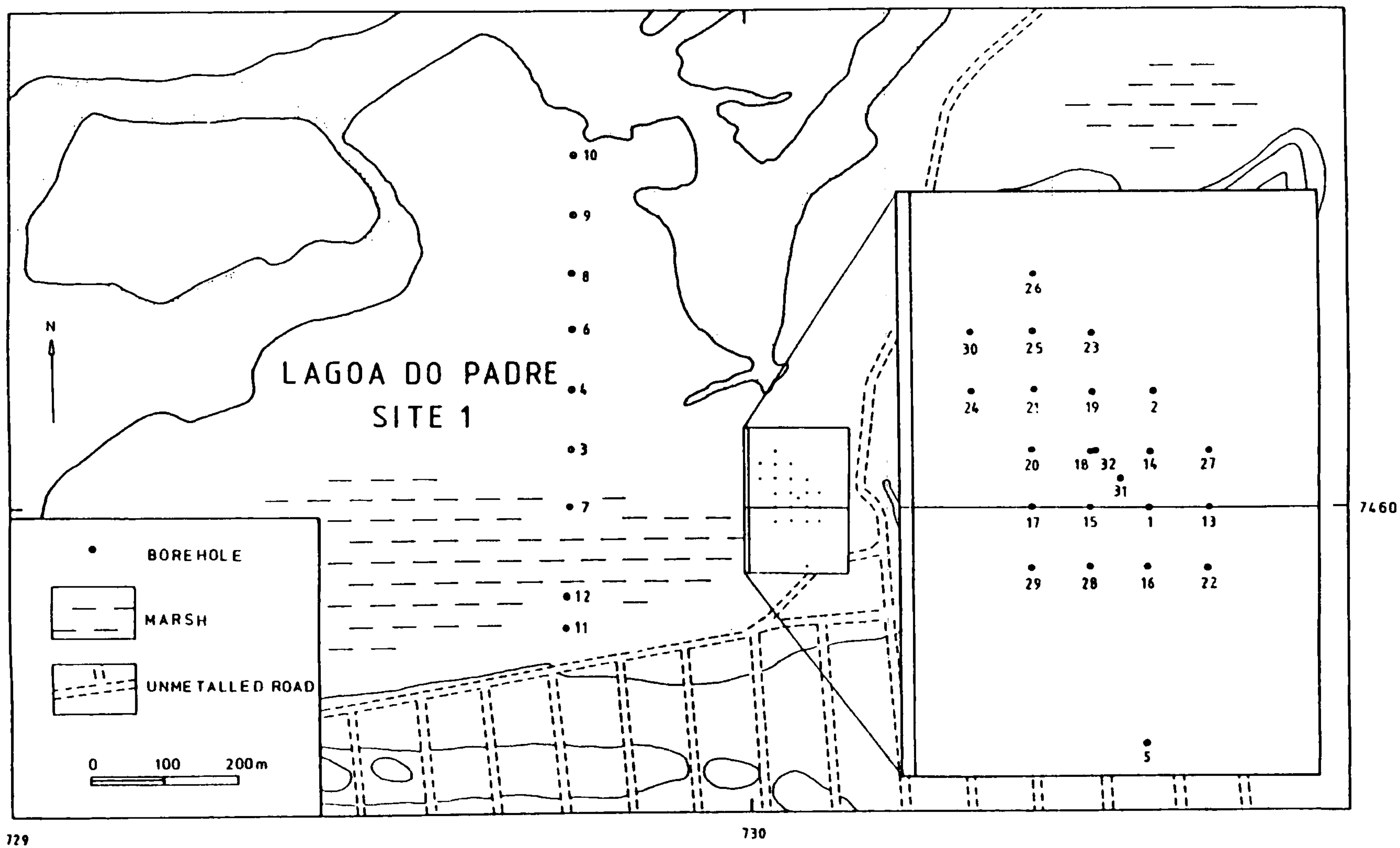


Figure 4.2 A map of Lagoa do Padre Site 1, showing the location of boreholes

well developed *restinga* vegetation. Behind the older barrier, at the eastern end of the lagoon, an area of relatively flat marshland has formed.

4.3.1 Presentation of results for Lagoa do Padre Site 1

Lagoa do Padre Site 1 is situated on the marshland at the eastern end of the lagoon. The locations of the 32 borings which were put down here are shown in Figure 4.2.

4.3.1.1 Stratigraphic analysis

The initial sampling strategy was to run four transects, perpendicular to the present coastline, 320 m apart and to sink boreholes at 80 m intervals along each transect. This strategy, which was designed to cover the marsh, was changed after completing two transects because the most meaningful sedimentary sequences were found in the southeastern corner of the marsh. The stratigraphy of this area, which was sampled on a 20 m grid, will be described first. The transect running across the marsh will then be described and, where possible related to that of the southeastern corner.

In the northeast of the intensively sampled area (boreholes LP-1/2, /23 and /27) the base of the sequence is a mottled white and olive yellow, kaolinitic clay with streaks of red. Small numbers of iron concretions, ranging from fine sand to fine gravel in size, are present. Exploratory borings showed that this extends northeastward and changes colour to mottled red and white.

At LP-1/23, as Figure 4.3 illustrates, this clay is overlaid by a virtually impenetrable, light grey, sandy, kaolinitic clay with well humified herbaceous roots. This is an easily recognizable stratum which, with the exception of LP-1/2 and /27, is found over all of this part of the site, sometimes with horizontally bedded plant detritus. It forms a linear depression running from northwest to southeast (Figure 4.4a). Due to the

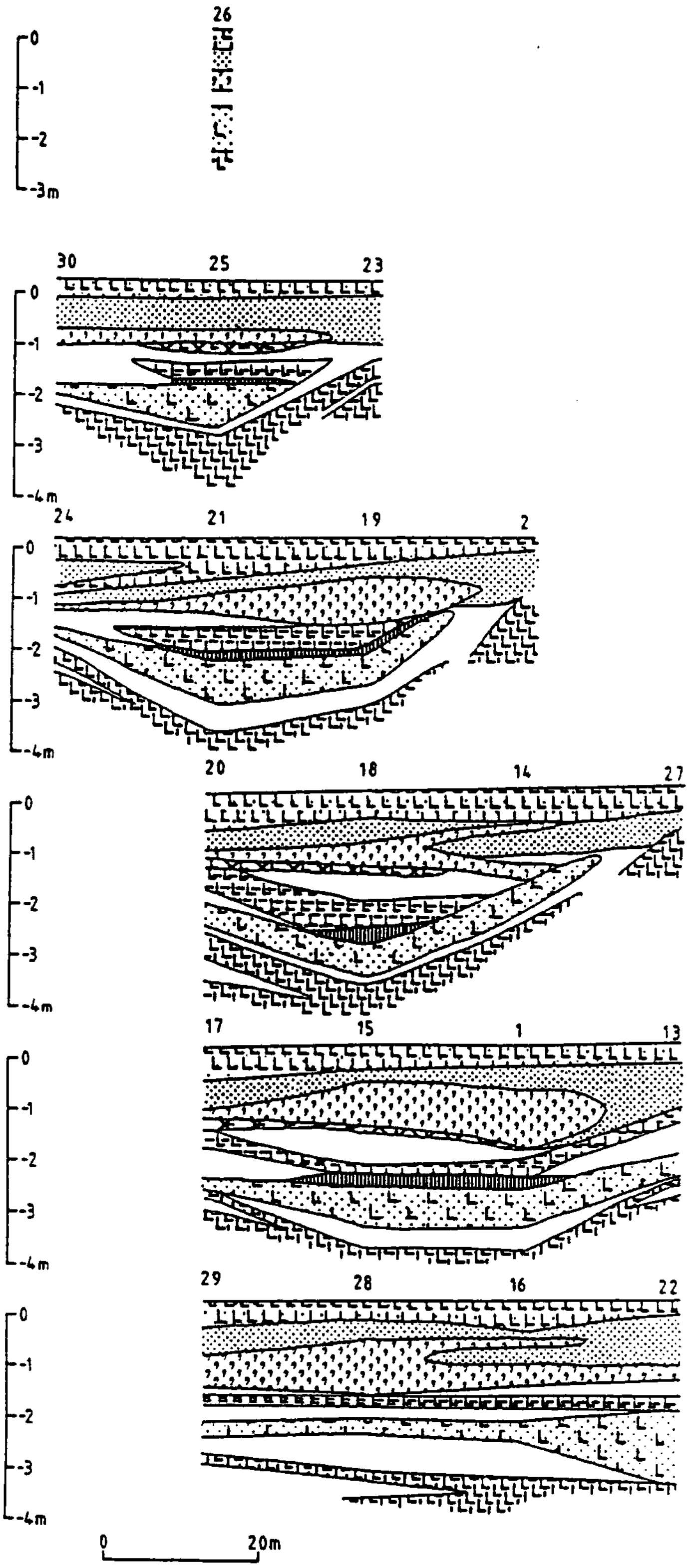


Figure 4.3 A diagram showing the relationship between the main sedimentary strata in the southeastern corner of Lagoa do Padre Site 1. See Appendix V for the key to this and other stratigraphic diagrams. In this diagram very variable strata are left blank.

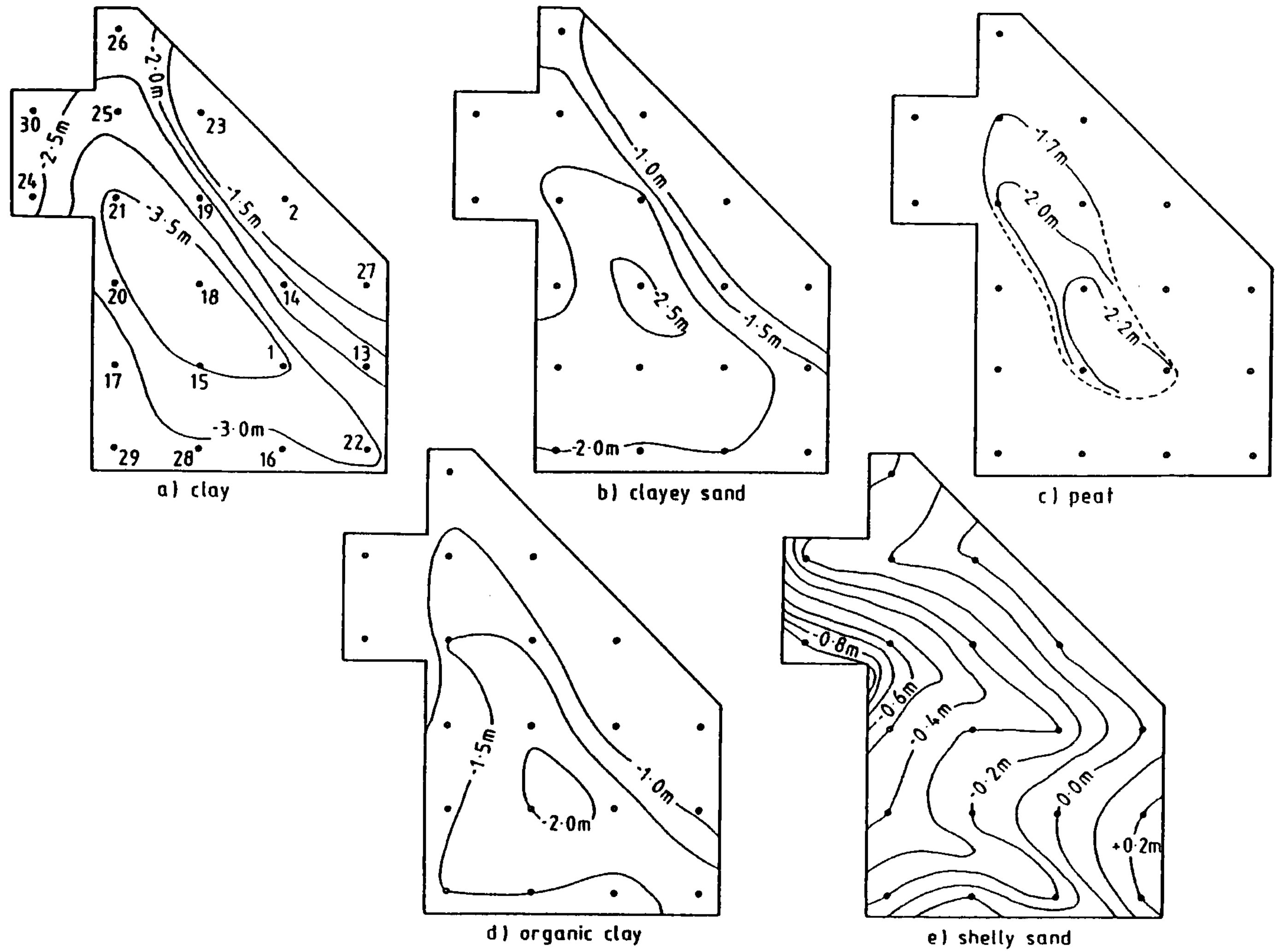


Figure 4.4 Maps showing the possible surface configuration of selected sedimentary strata in the southeastern corner of Lagoa do Padre Site 1

impenetrable nature of this clay, only one borehole (LP-1/1) was sunk to any depth through it. This borehole revealed that at an altitude of -4.3 m there is a transition from clay to light grey, gravelly sand which extends for 1.08 m. Below this is 1.24 m of similar, but less indurated clay. Several strata can be identified within both clays, some of which contain lenses of more indurated clay or clayey sand. At an altitude of -6.6 m there is another transition to light grey, gravelly sand.

The deposits immediately overlying the stiff clay, particularly in the depression, vary from borehole to borehole and range from clay to sandy gravel. Overlying these, however, and in some cases directly over the stiff clay is a stratum which can be identified over most of this part of the site (excluding LP-1/2, /23 and /27). This stratum is a light to dark grey, clayey sand, composed of three parts sand and one part clay. It modified the shape of the depression (Figure 4.4b) but the northwest-southeast axis is still clearly present. The relative position of the stratum is shown in Figure 4.3.

Above this stratum is a small body of peat (2,280 m^2) which has a mean recorded thickness of 30 cm. The peat, which characterizes this area of the site, dips from an altitude of -1.77 m towards the southeast, at an angle of 1°, then flattens. It follows the same linear axis as the depression in the lower clay (Figure 4.4a and c.). The peat is predominantly a dark reddish brown or very dark brown, herbaceous peat with some woody detritus and woody roots (up to 50% by volume) at two points close to its periphery.

Where the grey, clayey sand is not covered by peat, it is overlaid by sand with a small clay fraction. Over much of the site the sand and peat have subsequently been sealed by an organic clay, generally composed of three parts clay and one part completely humified organic matter. The extent of this deposit is shown in Figures 4.3 and 4.4d. The northwest-southeast depression is still evident.

The organic clay is partially covered by a more highly organic clay of variable thickness which is, in turn, covered by a muddy clay containing small concentrations of shell fragments including *Anomalocardia brasiliana* (Gmelin). This extends from the west and thins towards the east (Figure 4.3). The whole area is then overlaid by quartz sand with varying proportions of *A. brasiliana* (Gmelin) fragments and single valves, forming up to 60% of the deposit. Also, particularly towards the east of the area, traces of fine to coarse gravel are present. The surface of this shelly sand is shown in Figure 4.4e, sloping from a high point in the east to a low point in the west. There is no suggestion of the northwest-southeast depression.

At the surface a very thin, clayey, herbaceous peat (2.5 cm thick) has developed. The sediment lying between this and the shelly sand is variable in composition, but is predominantly a sandy clay and, like the shelly sand, dips from east to west.

Figure 4.5 illustrates a northwest-southeast transect, approximately along the axis of the depression, and shows the relationship between LP-1/31, LP-1/32 (recovered for laboratory analysis) and adjacent cores. At LP-1/31 there is no peat at depth, but an organic layer composed of equal proportions of herbaceous plant detritus and fine detrital mud. At LP-1/5, which was sunk close to the barrier, the stratigraphic column is dominated by sand; clay is present in all strata below -4.77 m altitude, but the thin (3-4 cm) clay dominated layers are different in character from those described in the intensively sampled area.

In the north-south transect across the widest part of the marsh (Figure 4.6) borehole LP-1/3 differs markedly from those to the north and south. At this

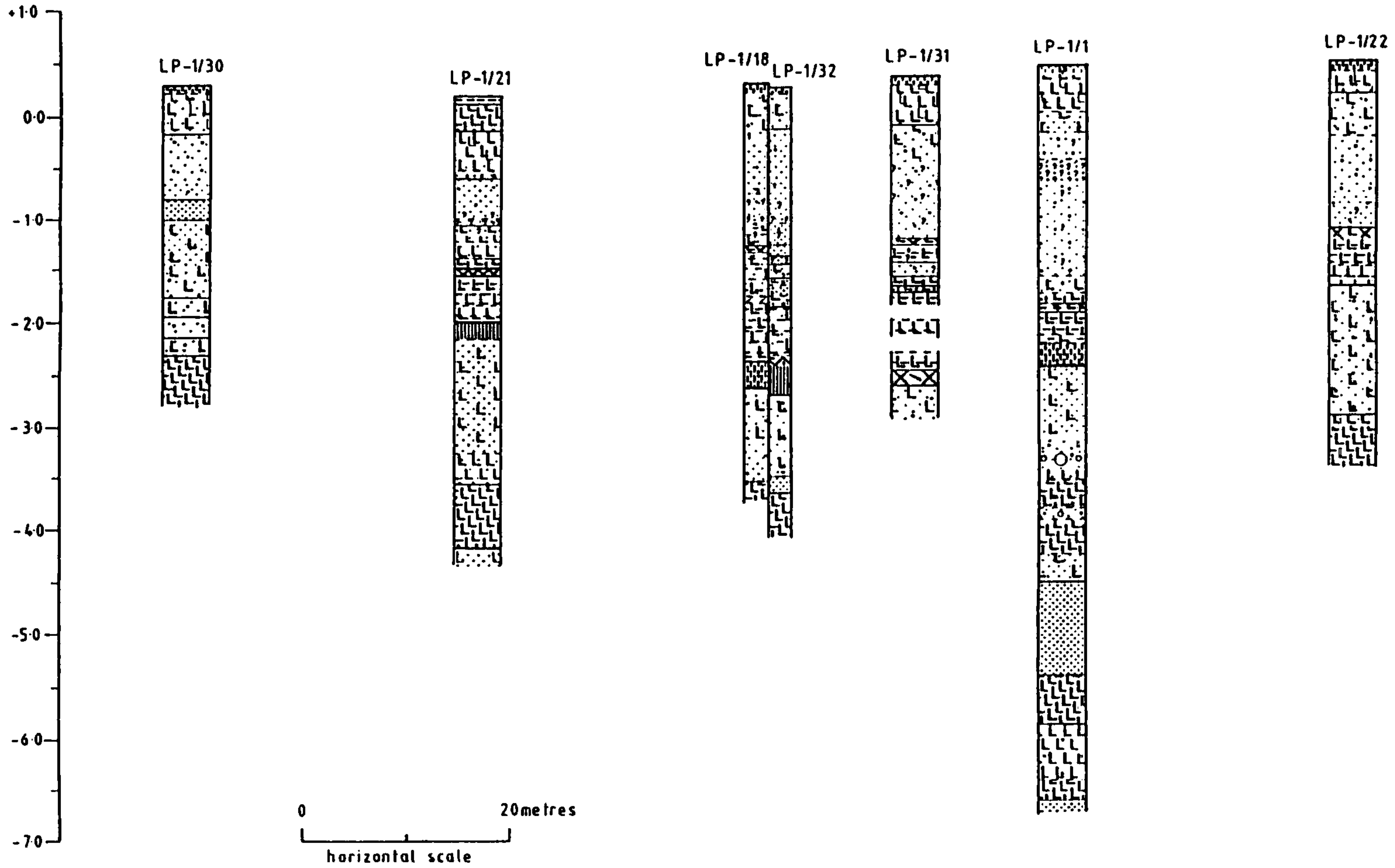


Figure 4.5 A diagram showing the stratigraphy along a northwest-southeast transect in the southeastern corner of Lagoa do Padre Site 1

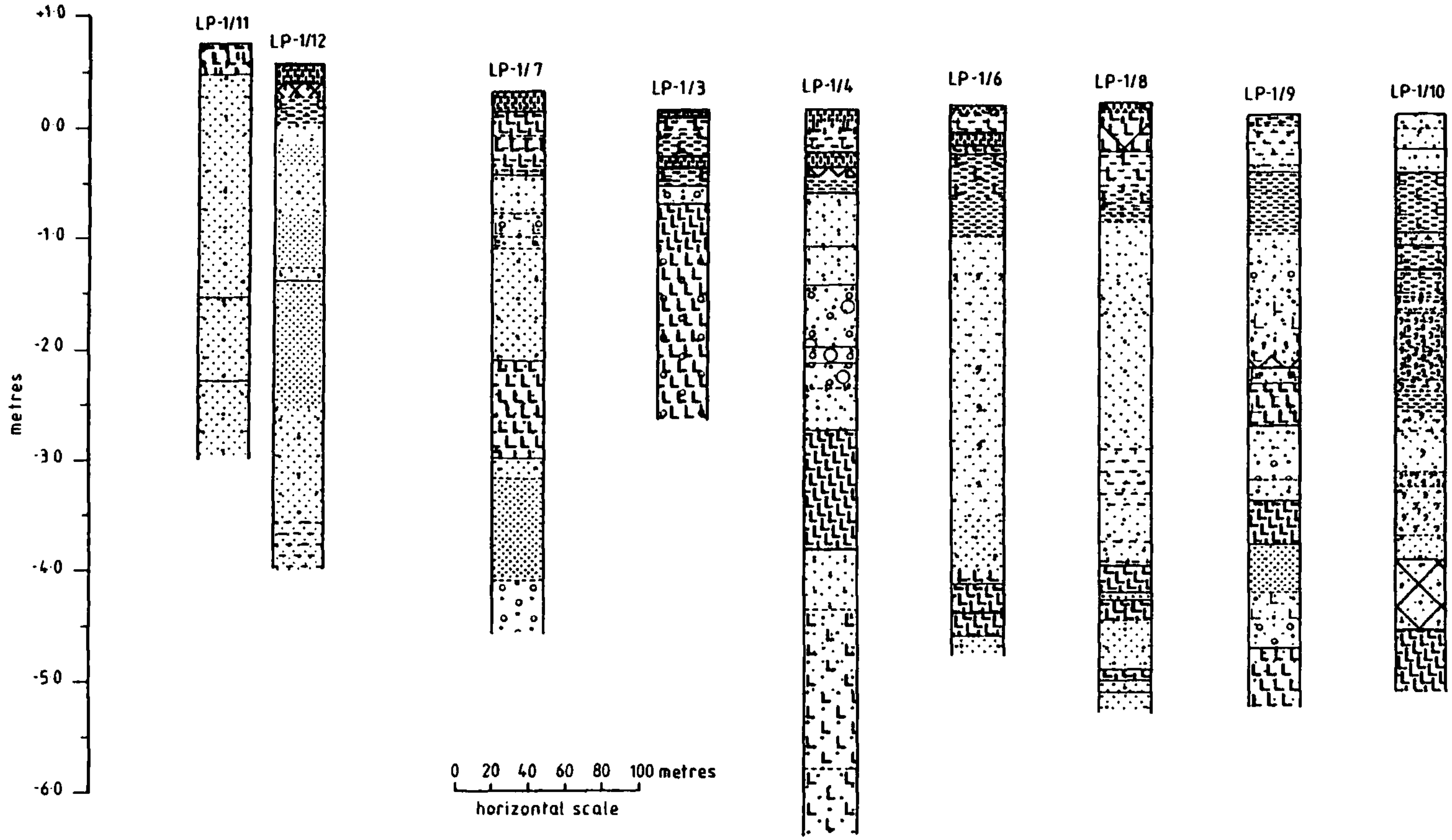


Figure 4.6 A diagram showing the stratigraphy along a north-south transect across the widest part of the back-barrier marsh of Lagoa do Padre Site 1

borehole, below -0.68 m altitude, there is a mottled white and olive yellow, kaolinitic clay which, below -1.14 m, contains red concretions of iron. It is similar to the clay identified in boreholes LP-1/2, /23 and /27. Above this clay only 84 cm of sediment has accumulated, yet along the remainder of the transect there are considerable depths of unconsolidated sediment.

North of LP-1/3 a stiff, sandy clay ranging in colour from light grey to light greyish brown, with plant fragments and occasionally fine gravel is found. From an altitude of -2.73 m at LP-1/4 it dips northward at an angle of 1°, then flattens before rising at an angle of 0.5° to LP-1/9. It then slopes down at an angle of 1° to -4.56 m altitude at LP-1/10. South of LP-1/3 the grey sandy clay recorded between -2.12 and -3.10 m altitude at LP-1/7 may represent the same stratum.

This clay is similar in nature to the virtually impenetrable, light grey, sandy clay identified over most of the southeastern part of the site, but cannot unequivocally be identified as the same stratum because of its variability and the distance between the two areas. An example of the variability can be seen in LP-1/6 and /8 where relatively thin clay strata (<15 cm thick) are intercalated with thin sandy strata. Also, it is interesting to note that at LP-1/6, towards the top of the clay, there are two strata composed of sandy-clay granules, 2 to 6 mm in diameter.

A body of sand and gravelly sand covers the clay at all boreholes. *Anomalocardia brasiliana* (Gmelin) shell fragments and single valves are found in the sand at LP-1/6 to an altitude of -3.58 m and at LP-1/10 down to -3.70 m. At LP-1/9 the sand body is divided by a clay stratum between -2.3 and -2.7 m altitude and as sandy, fine detrital mud and between -2.08 and -2.15 m. Over this part of the site the sand body ranges in thickness from 1.7 to 3.0 m.

Above the sand, the sedimentary sequence is dominated by organic deposits, either in the form of fine detrital mud or herbaceous peat. These predominantly organic strata are intercalated by inorganic deposits which are generally fine grained. These mostly organic sediments are generally found above -1.0 m altitude, but at LP-1/10 are found down to -2.58 m altitude. *Anomalocardia brasiliana* (Gmelin) shell fragments and single valves are present in the fine detrital mud between -1.30 m and -2.58 m altitude.

The stiff, sandy, clay stratum was not detected in the two southernmost boreholes of the transect. These are dominated by sand, with traces of gravel in some strata.

4.3.1.2 Particle size analysis

Particle size analysis was carried out on core LP-1/32. A tabular presentation of the results is in Appendix III, together with a detailed stratigraphic description of the borehole. A comparison of the two shows a generally good agreement between the field description and the laboratory analysis and shows that *Grana arenosa* is dominated by medium sand.

There are, however, several strata where the field description differed from the particle size analysis. Stratum 1 (As4, Ga+) contained 21% silt, and the formulation would be more accurately As3, Ag1, Ga+. In stratum 3 (Ga2, Gs1, As1) the clay content is only 10%, but the field description still represents the best coding. Stratum 6 (As2, Sh1, Ga1) requires subdivision - in the upper part the main inorganic constituents are Ga (43%), Ag (32%) and As (21%) while in the lower part they are Ag (64%), As (21%) and Ga (14%). In stratum 7 (Ld^{3}3,As1) the mineral fraction is actually dominated by sand, although this is biotite mica, not quartz. Finally stratum 8 (Ga2, As1, Sh1) contains 28% silt which was not noted.

The majority of these differences relate to the strata which have not been traced over the site, but the virtually impenetrable, light grey, sandy, kaolinitic clay should possibly now be described as a light grey, silty, kaolinitic clay with sand. It is possible that the field description was correct for the sample, but not the layer. Also particle size analysis tends to homogenize differences within a layer.

4.3.1.3 Roundness analysis

The results of the roundness analysis carried out on core LP-1/32 are presented in Table 4.2. Fine, medium and coarse sands were assessed separately, then taking into account the relative proportions of each sand size category in each stratum, weighted means were calculated.

The works of Beal and Shepard (1956) and Waskom (1958), in which only the fine sand class was used, reveal that there can be considerable disparities between the roundness characteristics of sediments sampled in similar environments. A comparison between these environments and Lagoa do Padre, however, is made more difficult because sediments at this site are generally coarser than those sampled around the northern Gulf of Mexico. The fine fraction at Lagoa do Padre, which corresponds to the fraction used in the above studies is not representative of the sediment, which is mostly medium sand (0.2 to 0.6 mm diameter).

Table 4.2: Roundness analysis results for the sand-sized fraction of core LP-1/32
(A = angular, SA = subangular, SR = subrounded)

Stratum	Troels-Smith Code [1]	Sphericity H = high L = low	Mean roundness of fine sand (0.06 - 0.2 mm)	Mean roundness of medium sand (0.2 - 0.6 mm)	Mean roundness of coarse sand (0.6-2.0 mm)	Weighted mean (0.06-2.0 mm)
18	Ga3,Gs1	H	0.21 (A)	0.44 (SR)	0.43 (SR)	0.42 (SR)
17	Ga3,Gs1	H	0.33 (SA)	0.41 (SR)	0.36 (SR)	0.40 (SR)
16	Ga4	H	0.26 (SA)	0.24 (A)	0.36 (SR)	0.25 (SA)
15	Ga4	H	0.23 (A)	0.33 (SA)	0.27 (A)	0.30 (SA)
14	Ga3,As1	H	0.25 (A)	0.30 (SA)	0.37 (SR)	0.30 (SA)
13	Ga4	H	0.25 (A)	0.29 (SA)	0.35 (SR)	0.29 (SA)
12	Ga3,As1	H	0.20 (A)	0.30 (SA)	0.24 (A)	0.27 (SA)
11	Ga4	H	0.25 (A)	0.28 (SA)	0.34 (SA)	0.29 (SA)
10	Ga2,As1,Ag1	H	0.20 (A)	0.30 (SA)	0.30 (SA)	0.27 (SA)
9	Ga4	H	0.21 (A)	0.30 (SA)	0.30 (SA)	0.28 (SA)
8	Ga2,As1,Sh1	H	0.24 (A)	0.24 (A)	0.29 (SA)	0.24 (A)
7	Ld^{3}3,As1	L	0.27 (SA)	0.27 (SA)	0.28 (SA)	0.27 (SA)
6b	As2,Sh1,Ga1	H	0.28 (SA)	0.25 (SA)	0.34 (SA)	0.27 (SA)
6a	As2,Sh1,Ga1	H	0.32 (SA)	0.35 (SA)	0.37 (SR)	0.34 (SA)
3	Gs2,Ga1,As1	H	0.25 (SA)	0.34 (SA)	0.27 (SA)	0.31 (SA)
2	Ga4	H	0.27 (SA)	0.36 (SR)	0.38 (SR)	0.36 (SR)
1	As4	H	0.26 (SA)	0.37 (SR)	0.39 (SR)	0.36 (SR)

1. See Appendix III for more detailed description.

4.3.1.4 Diatom analysis

Diatom analysis was carried out on two cores at this site; LP-1/31 and LP-1/32. A second core (LP-1/31) was counted to determine whether impoverished zones were extra local and to assess between-core variation.

From the base of the LP-1/32 stratigraphic column to just below the surface of stratum 3, the light to dark grey clayey sand depicted in Figure 4.4b, there is an impoverished zone (Figure 4.7). The uppermost level of stratum 3 (LDSP LP-1/32a) is dominated by fresh-brackish and brackish-fresh diatoms. The fresh and fresh-brackish taxa are predominantly *Eunotia* Ehr. (particularly *E.pectinalis* Ehr. and *E. tenella* (Grun.) Hust.) and *Pinnularia* Ehr. (notably *P.sudetica* Hils.). This zone is also characterized by a decreasing presence of the marine planktonic *Cyclotella striata* var. *americana* A.Cl..

The peat stratum is marked by LDSPs LP-1/32b to LP-1/32d. LP-1/32b is fresh, dominated by *Pinnularia sudetica* Hils.; LP-1/32c is fresh-brackish, dominated by *Eunotia tenella* (Grun.) Hust. and *Nitzschia amphibia* Grun.; while LP-1/32d is fresh and brackish-fresh, dominated by *Navicula arvensis* Hust., *Cyclotella meneghiniana* Kütz. and *Nitzschia scalaris* (Ehr.) W. Sm.. The latter phase is also characterized by a rise in brackish, brackish-marine and marine benthic diatoms.

Stratum 6, which is the organic clay stratum identified in Figure 4.4 is marked by four LDSPs: LP-1/32e, LP-1/32f, LP-1/32g and LP-1/32h. Phases LP-1/32e and g are very similar, both being heavily dominated by the fresh *Navicula arvensis* Hust.. LP-1/32f, at -2.17 m altitude, is characterized by a marked increase in marine benthic diatoms, notably *Navicula amphipleuroides* Hust. and *Opephora parva* (V.H.) Krasske, but fresh diatoms, dominated by *N. arvensis* Hust., make up 60% of the assemblage.

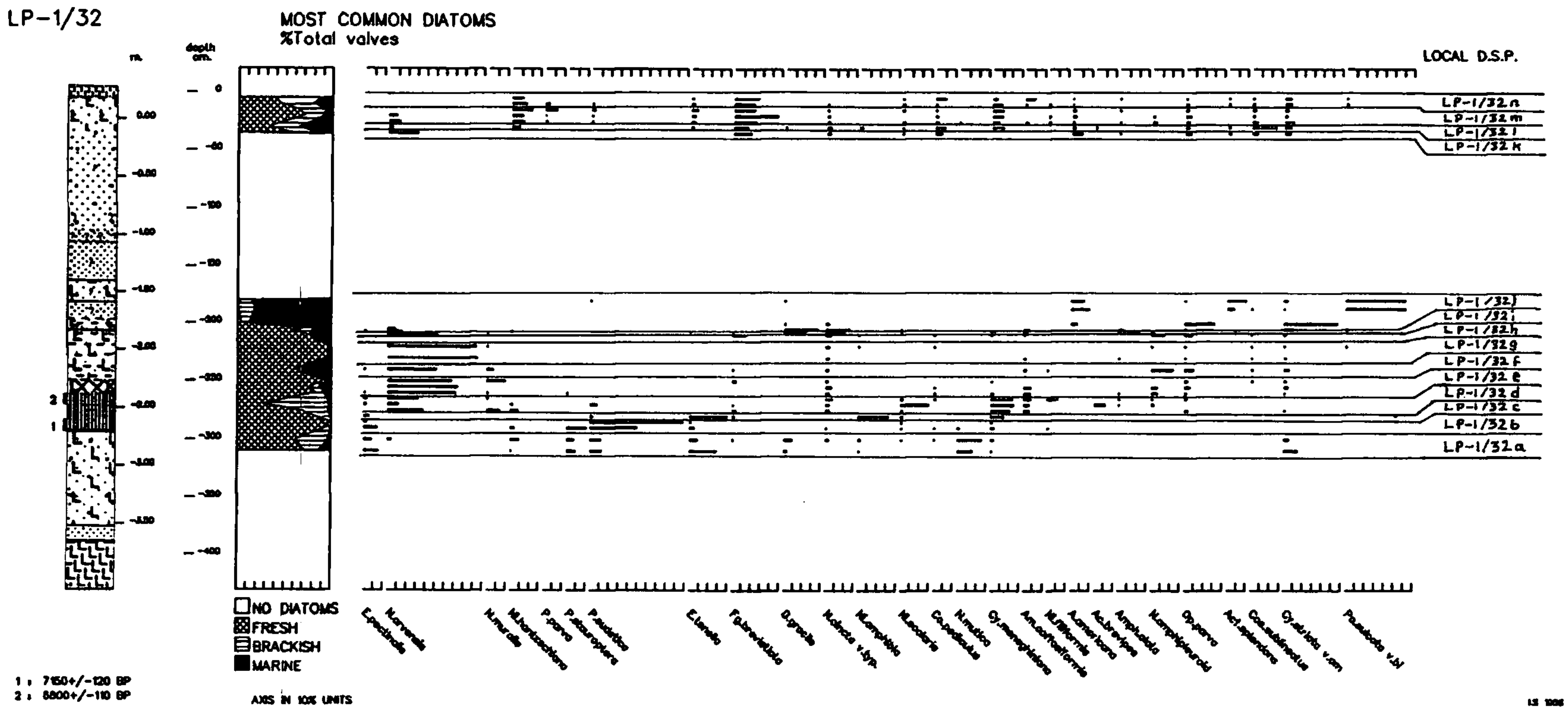


Figure 4.7 A diatom diagram showing the most common diatoms enumerated in core LP-1/32 (see Appendix IV for the rare diatoms)

LP-1/32h which marks the top of the stratum 6 and stratum 7, a clayey mud, is also predominantly fresh. It is, however, characterized by an increased marine influence, mostly of *N. amphipleuroides* Hust. and *Amphiprora alata* Kütz..

The lowest part of stratum 8 is marked by LP-1/32i which is characterized by the dominance of fresh-brackish *Gomphonema gracile* Ehr. and *Navicula cincta* var. *typica* A.Cl.. The top of stratum 8 and overlying strata to the base of stratum 12 are represented by LP-1/32j, although a sample taken at -1.62 m altitude (at the boundary between strata 10 and 11) did not contain countable concentrations of diatoms. This is a marine phase dominated in turn by *Cyclotella striata* var. *americana* A.Cl. and *Paralia sulcata* var. *biseriata* Grun.. At the top of the zone the valves are predominantly fragmented. Above this, between -1.57 m and -0.11 m altitude, there is a second impoverished zone.

Diatoms are again found in countable concentrations in the dark grey silty clayey sand (stratum 19) which forms the uppermost inorganic layer. Four LDSPs are recognized here (LP-1/32k to LP-1/32n). LP-1/32k is dominated by freshwater diatoms; *Navicula arvensis* Hust. and *Fragilaria brevistriata* Grun., with a notable presence of brackish *Terpsinoë americana* (Bail.) Ralfs. LP-1/32l is characterized by a rise in planktonic marine diatoms, the most evident of which is *Coscinodiscus sublineatus* Grun.. The broad fresh, brackish and marine groups are equally represented (33%, 32% and 35% respectively). LP-1/32m is dominated by the fresh *Nitzschia hantzschiana* Rabh. and the fresh-brackish *F. brevistriata* Grun.. Most of the diatoms are fresh but brackish and marine diatoms are also present. In LP-1/32n the same species are dominant as in LP-1/32l, but the assemblages are more brackish.

For the reasons stated above, diatom analysis was also carried out on core LP-1/31. As with LP-1/32 there is an impovershed zone at the base of LP-1/31 (Figure 4.8) which extends to the base of the organic horizon (stratum 2). LP-1/31a which marks the base of the stratum is dominated by the fresh diatom *Navicula arvensis* Hust., but there is a marked presence of marine diatoms, the most conspicuous of which is the benthic *N. amphipleuroides* Hust., but *N. brachium* Hust., *Opephora parva* (V.H.) Krasske and *Cyclotella striata* var *americana* A.Cl. are also present.

Salinity phase LP-1/31b extends through the organic stratum and the lower levels of the overlying organic clay (stratum 3). This zone is predominantly fresh, but with a brackish presence. Within the organic stratum, *Navicula* Bory species, notably *N. arvensis* Hust., *Eunotia* Ehr. species, particularly *E. pectinalis* (Dillwyn) Rabh., *Pinnularia* Ehr. species, especially *P. stauroptera* (Rabh.) Cl. and *Nitzschia* Hassal species are dominant. In the clay immediately over stratum 2 similar species, with the exception of *Navicula* Bory species, dominate, then *Navicula* Bory species particularly *N.arvensis* Hust. and *N.cincta* var *typica* A. Cl. are most common.

LP-1/31c at -2.34 m altitude, is predominantly fresh, but with an increased number of marine diatoms. It is characterized by *N. arvensis* Hust. and marine benthic *N. amphipleuroides* Hust.. This is similar to phase LP-1/32f. Above this phase, also in stratum 3, LP-1/31d is essentially similar to LP-1/32n. Phase LP-1/31e marks the transition from stratum 3 to stratum 4. It is predominantly fresh but with a marked increase in marine diatoms. It is similar to LP-1/32h in that *Gomphonema gracile* Ehr. and *Navicula cincta* var. *typica* A.Cl. are common. *Amphiprora alata* Kütz. is present, but *Opephora parva* (V.H.) Krasske *and Cyclotella striata* var *americana* A.Cl. are more abundant.

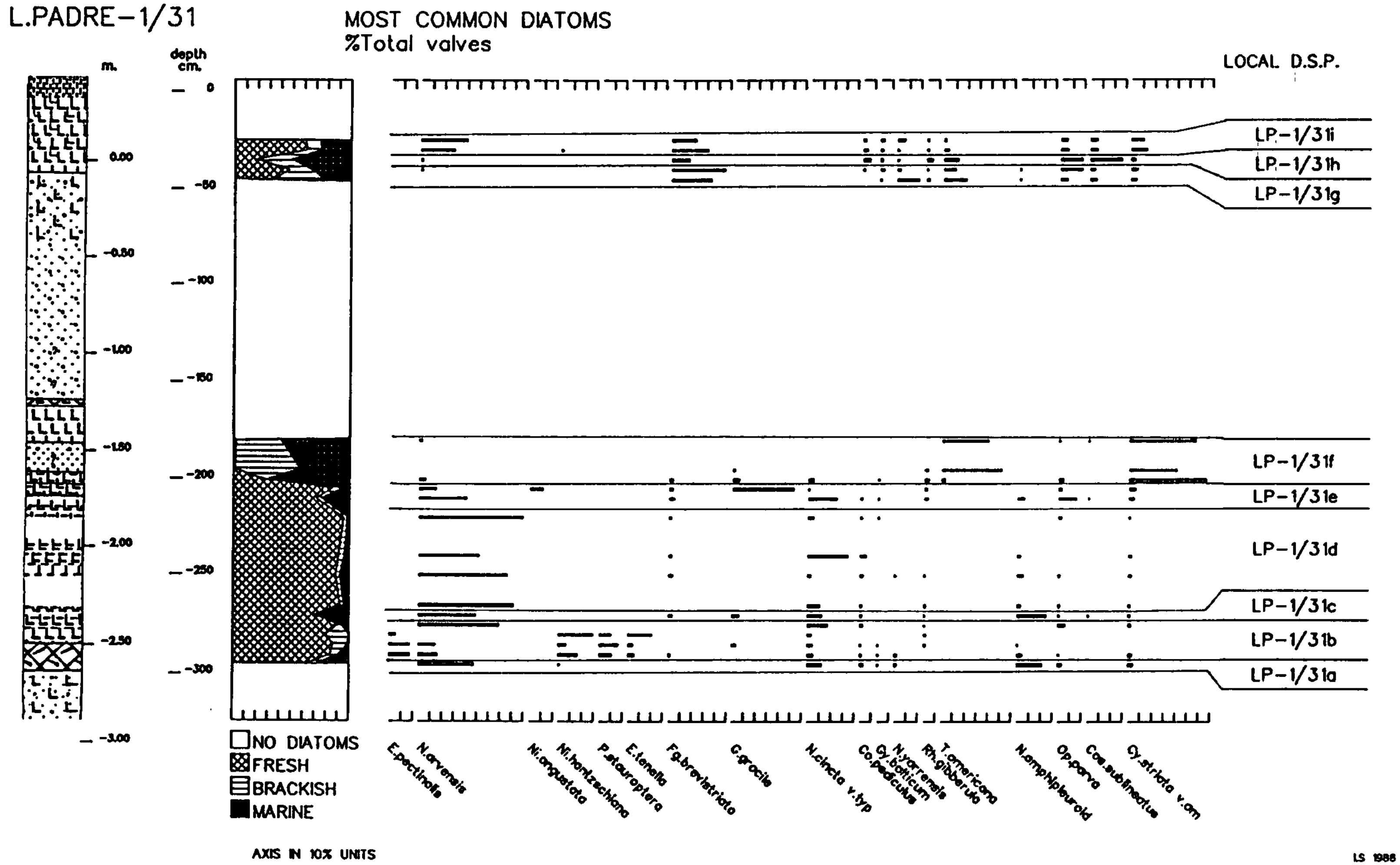


Figure 4.8 A diatom diagram showing the most common diatoms enumerated in core LP-1/31 (see Appendix IV for the rare diatoms)

In LP-1/31f marine and brackish diatoms dominate. *Cyclotella striata* var. *americana* A.Cl. dominates the marine taxa and *Terpsinoë americana* (Bail.) Ralfs the brackish taxa. The phase extends from stratum 5, a muddy, sandy clay, to the base of stratum 7, the muddy, clay stratum containing *Anomalocardia brasiliana* (Gmelin) fragments. The shelly sand of stratum 6 is, however, devoid of diatoms. It is notable that this phase is markedly more brackish than LP-1/32i. Above this phase, between -0.09 and -1.44 m altitude there is a second impoverished zone.

This impoverished zone extends to the base of stratum 12, the dark grey, sandy clay forming the uppermost inorganic horizon. Three salinity phases are recognized within this clay (LP-1/31g to LP-1/31i). LP-1/31g, which is dominated by *Fragilaria brevistriata* Grun. also has significant counts of *Terpsinoë americana* (Bail.) Ralfs. Through the zone there is an increase in the presence of marine *Opephora parva* (V.H.) Krasske. LP-1/31h is characterized by an increased marine presence notably by *Coscinodiscus sublineatus* Grun.. Finally, LP-1/31i shows a decline in the marine and particularly brackish diatoms. It is dominated by *Navicula arvensis* Hust. and *Fragilaria brevistriata* Grun..

4.3.2 Presentation of results for Lagoa do Padre Site 2.

Lagoa do Padre site 2 is situated in a narrow sediment filled bay on the landward side of the lagoon and is separated from it by a sand barrier (Figure 4.1) It is at a higher altitude than site 1.

4.3.2.1 Stratigraphic analysis

There are 12 boreholes at this site (Figure 4.9). The sampling interval varies between 5 and 50 m, depending on the complexity of the stratigraphy.

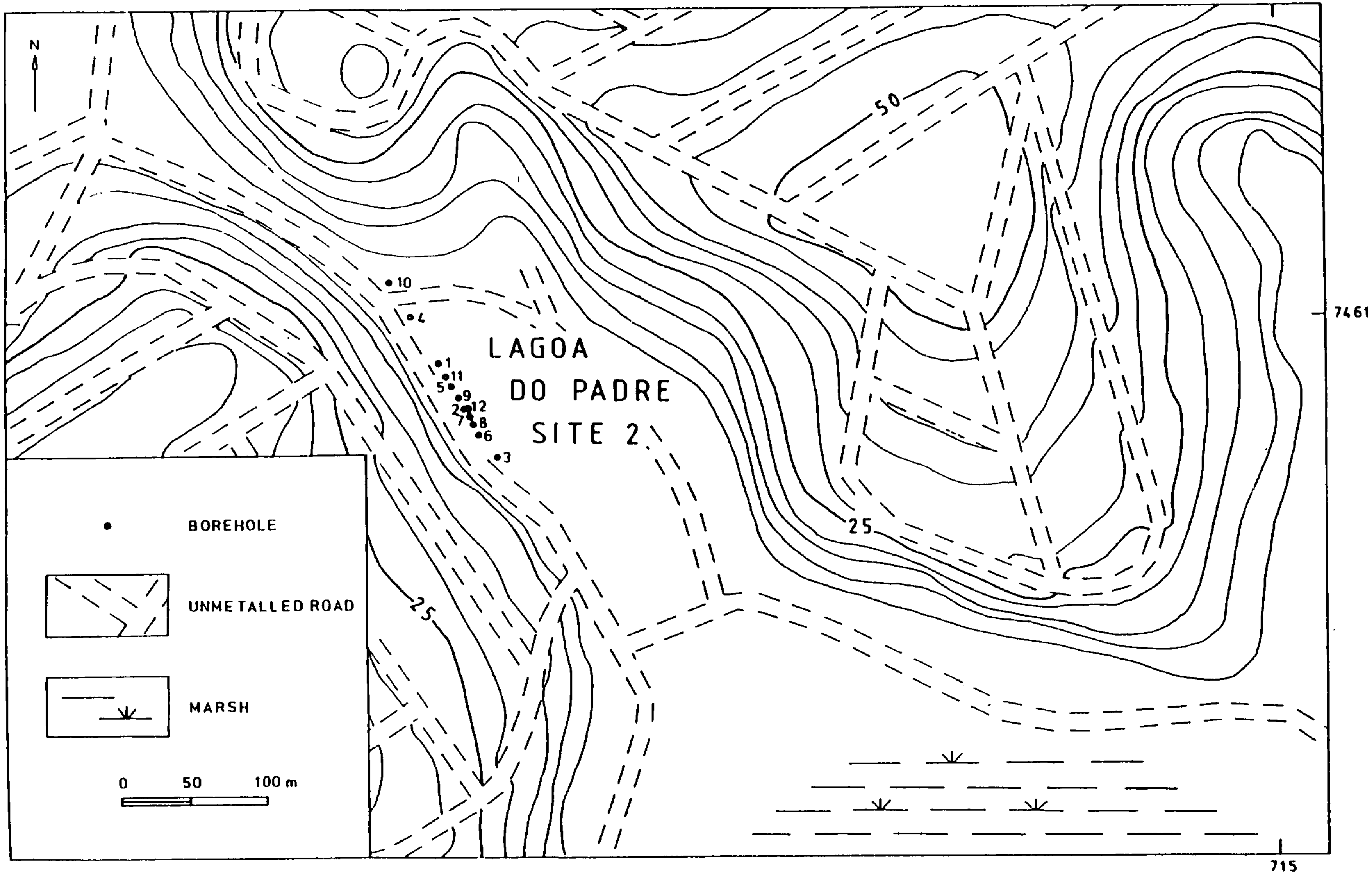


Figure 4.9 A map of Lagoa do Padre Site 2, showing the location of boreholes

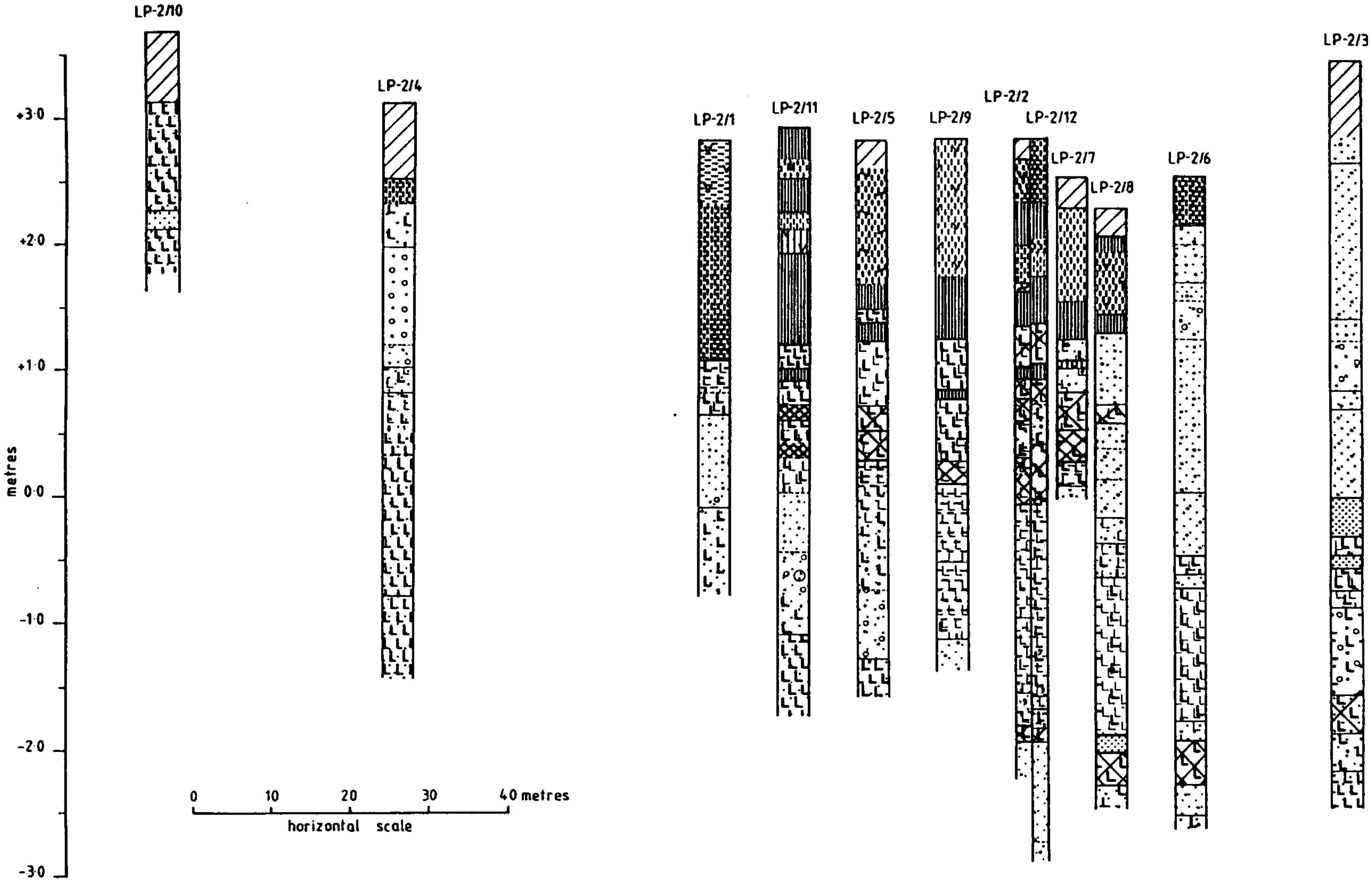


Figure 4.10 A diagram showing the stratigraphy of Lagoa do Padre Site 2

The most northerly borehole (LP-2/10), which is close to the scarp, exhibits 1.36 m of unconsolidated sediment covering a weak red, kaolinitic clay containing partially weathered mica, orthoclase felspar and quartz. (Figure 4.10). Moving southeast from the scarp, a virtually impenetrable light brownish grey to dark grey, sandy, clay stratum is found at depth. Small quantities of partially humified, herbaceous and fine woody roots are found at LP-2/4 and a woody root approximately 12 mm in diameter was recovered from LP-2/5. The stratum slopes from 0.08 m altitude at LP-2/4 to -1.31 m at LP-2/5.

Immediately over the weak red clay and intermittently covering the indurated clay is a grey, sandy, clay stratum which can be traced across the site. From an altitude of 2.10 m at LP-2/10 it dips gradually, at an approximate angle of 1.8°, to -2.25 m altitude at LP-2/3. The average recorded thickness of this layer is 28 cm (standard deviation = 7 cm) These strata are overlaid by a sand bed with concentrations of gravel, notably at the base of LP-2/4 where approximately 75% of the deposit is fine gravel. The sand reaches a maximum elevation of 2.29 m at LP-2/4. At the seaward end of the transect (LP-2/2 and LP-2/3) the sand is intercalated with a stratum varying from clayey, fine detrital mud to muddy clay.

Between LP-2/11 and LP-2/3, the sand is covered by a dark to very dark grey, muddy, clayey silt with woody and herbaceous plant fragments and traces of sand. At LP-2/2 between -1.31 and -1.81 m altitude the sediment contains a higher proportion of sand and fragments of *Anomalocardia brasiliana* (Gmelin). These shells are also found between -0.99 and -1.58 m in borehole LP-2/12. To the seaward the silt is overlaid by a considerable thickness of sand which intercalated with silty, clay strata at its base. To the landward it is covered by dark greyish brown, silty, fine detrital mud.

Overlying the detrital mud the sediment is of variable composition, but is predominantly organic, silty clay with some sandy strata (particularly to the seaward) and organic levels. Over these a peat has developed. It is a heterogeneous, generally well humified peat, consisting of very dark brown humified herbaceous material at the base, but also including pale brown, slightly humified, woody, herbaceous material. A silty, sandy clay is intercalated in the basal peat to the seaward of LP-2/1.

4.3.2.2 Particle size analysis

Particle size analysis was carried out on core LP-2/12. A detailed stratigraphic description of this core, together with a tabular presentation of the results is in Appendix III. In several cases the sediment was inadequately described in the field, but generally there is good agreement.

In stratum 3 (As2, $Ld^{3}2$, Ag+) the inorganic fraction is dominated by medium and fine sand (Ga 50%, Ag 28%, As 13%, Gs 9%) so the formulation Ga2, $Ld^{3}2$, Ag+, As+, Gs+ would be preferable. Stratum 7 is markedly more sandy towards its top than at its base, which was not noted in the field. The inorganic fraction of stratum 9 ($Ld^{3}2$, As2, Ag+, Ga+) is, as was the case with stratum 3, dominated by sand (Ga 48%, As 18%, Gs 17%, Ag 16%) and the formulation $Ld^{3}2$, Ga2, As+, Gs+, Ag+ would be preferable. This stratum provides an example of one of the problems of the use of Troels-Smith (1955) scheme discussed in Chapter 2. In strata 11 and 13, medium sand should replace the recorded silt component.

Over the site as a whole, the major implication of these inaccurate descriptions is that the sediment between the detrital mud and peat is more sandy then was appreciated. This also applies to the sediment intercalating the basal peat.

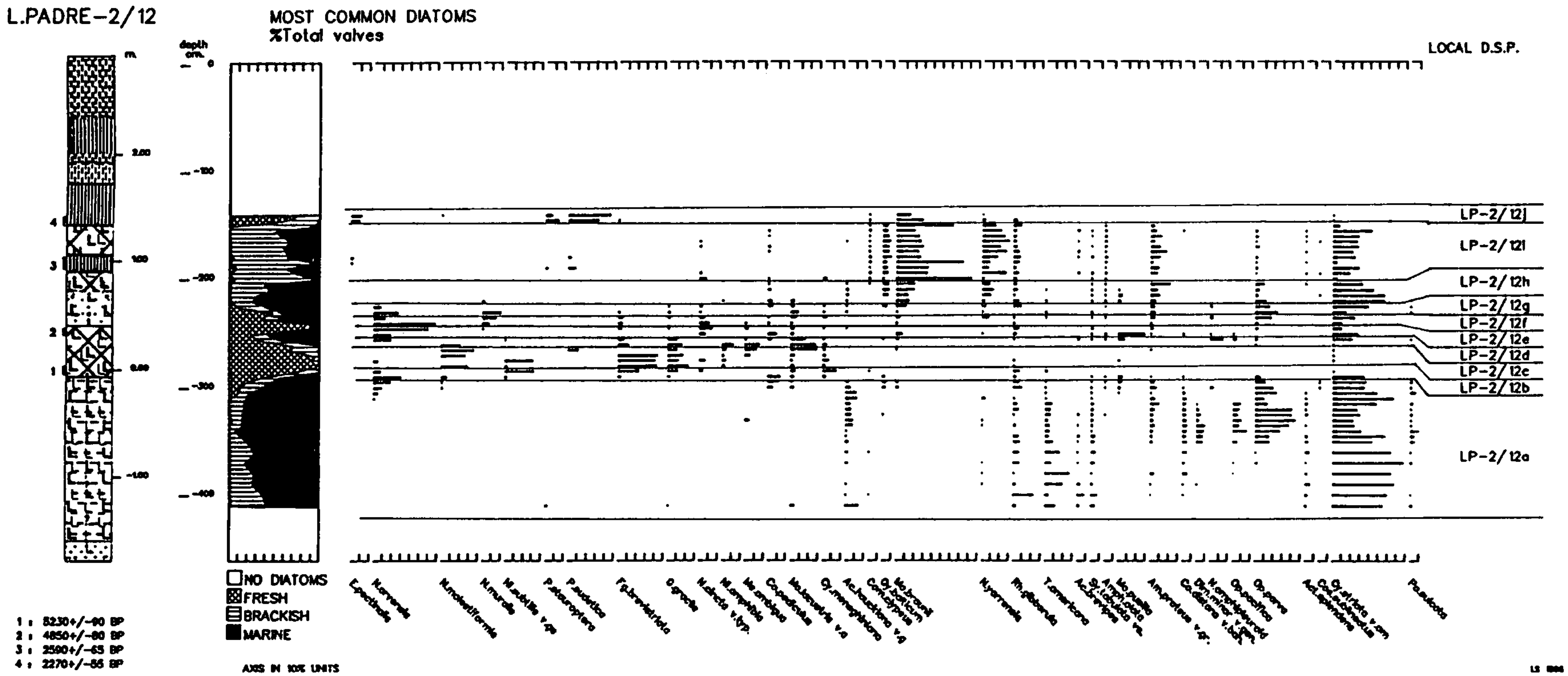


Figure 4.11 A diatom diagram showing the most common diatoms enumerated in core LP-2/12 (see Appendix IV for the rare diatoms)

4.3.2.3 Diatom analysis

Diatom analysis was carried out on core LP-2/12 (Figure 4.11). At the base of the core, below -1.27m, there is an impoverished zone containing no diatoms. Valves first appear mid-way through stratum 6, the very dark grey, muddy, clayey silt with *Anomalocardia brasiliana* (Gmelin) shell fragments. Salinity phase LP-2/12a, which is dominated by marine diatoms, extends from mid-stratum 6 to almost the top of stratum 7 (also very dark grey, muddy, clayey silt). The majority of the phase is dominated by planktonic *Cyclotella striata* var. *americana* A.Cl., but between -0.37 and -0.57 m altitude it is dominated by benthic *Opephora* Petit species; particularly *O.parva* (V.H.) Krasske but also *O. pacifica* (Grun.) Petit. Below this level *C. striata* var. *americana* A.Cl. is very clearly dominant, while above there is still a significant presence of *O. parva* (V.H.) Krasske.

It is important to relate this variation to changes in the grain size characteristics of stratum 7, as indicated by particle size analysis. Stratum 6 and lower stratum 7, where *C. striata* var. *americana* A.Cl. is clearly dominant, is a clayey silt with almost identical grain size distribution (Ag 60-62%, As 25-26%, Ga 13%). The part of stratum 7 dominated by *Opephora* Petit species is markedly more sandy (Ag 40%, Ga 36%, As 16%, Gs 6%). Above this the sediment is still sandy, but there is an increased clay content (Ag 42%, Ga 30%, As 22%, Gs 6%).

The top of the stratum 7 is marked by LP-2/12b. This phase while still predominantly marine and brackish, is characterized by a rise in the fresh brackish count. *C. striata* var. *americana* A. Cl. is dominant but there is a marked presence of fresh *Navicula arvensis* Hust..

LP-2/12c is a fresh to fresh-brackish phase dominated by *Fragilaria brevistriata* Grun. with *Navicula molestiformis* Hust., *Nitzschia subtilis* var.

genuina Grun. and *Gomphonema gracile* Ehr.. LP-2/12d is also essentially fresh, but with a much increased brackish-fresh count. *N.molestiformis* Hust. is the dominant fresh species and *Mastogloia lacustris* var. *alpina* Brun accounts for the high brackish-fresh count. These fresh phases correspond to stratum 8, the dark greyish brown detrital mud identified over most of the site. LP-2/12d marks the upper most 10 cm of the stratum.

LP-2/12e is characterized by a marked rise in marine and marine-brackish diatoms; together forming approximately 50% of the enumerated valves. *Cyclotella striata* var. *americana* A.Cl., *Mastogloia pusilla* Grun. and *Navicula amphipleuroides* Hust. dominate the marine component, while *Navicula arvensis* Hust. dominates the fresh component. This phase relates to stratum 9, a greyish brown, sandy, detrital mud. LP-2/12f is essentially fresh and dominated by *N. arvensis* Hust.. It marks the transition between stratum 9 and stratum 10, a clayey sand, where LP-2/12g comprises approximately equal proportions of fresh (35-48%) and marine (41-45%) diatoms. The marine taxa are dominated by *Opephora parva* (V.H.) Krasske and *C. striata* var. *americana* A.Cl., while the fresh are dominated by *N.arvensis* Hust. and *N. muralis* Grun..

This phase is superseded by LP-2/12h which is marine and brackish, with marine valves ranging from between 57 and 73% of the assemblage. *Cyclotella striata* var. *americana* A. Cl. is dominant. LP-2/12h extends from the clayey sand of stratum 10 through most of the sandy clay of stratum 11. LP-2/12i is also marine and brackish, but here brackish diatoms dominate (50-90%). *Mastogloia braunii* Grun. and *Navicula yarrensis* Grun. are the most common brackish diatoms. This phase extends from stratum 11, just below the basal peat stratum, through the peat and the overlying sandy, organic clay (stratum 13).

The peat which has accumulated over the clay is marked by fresh phase LP-2/12j which is dominated by *Pinnularia sudetica* Hils.. Brackish diatoms, notably *M.braunii* Grun., are present.

4.3.3 The sedimentary history of Lagoa do Padre

At site 1 three boreholes revealed mottled white and olive yellow, kaolinitic clay with iron concretions. This is believed to be a pallon horizon which can form during the development of a Ferralsol, as described by FitzPatrick (1983). The pallon would be one of the deeper horizons because, according to FitzPatrick, this is where the moisture required for its formation would be found. Thus its presence immediately below water-laid sediment implies that erosion, possibly of a considerable thickness of soil has occurred prior to sedimentation. It is impossible to speculate about the thickness of soil removed, as a lowering of the surface is characteristic of Ferralsol development, but it is interesting to note that such erosion is usually attributed to a change from a wet to a dry climatic regime.

Van der Hammen (1981), referring to the most recent glacial period, described from *c.* 50000 to 25000 BP as a wet phase in the northern Andes, from *c.* 21000 to *c.* 12500 BP as a dry phase in the Andes and in other tropical areas of the world, then post *c.* 12500 as a wetter phase. For southern Chile, Heusser *et al.* (1981) described the period around 43000 BP as a relatively wet and warm interstadial, from before 31000 BP to at least 14000 BP as a drier and colder stadial, and post 14000 BP as warmer and wetter. The exposure of the pallon may therefore have occurred during the most recent stadial, but could equally have occurred during one of the previous glacial maxima.

The virtually impenetrable, light grey, silty, kaolinitic clay with sand, identified in the southeast of site 1 and tentatively over most of this site, was deposited in a low energy environment. This is indicated by the preponderance of clay (>70%) and the presence of horizontally bedded plant debris. Unfortunately the presence of kaolinite, which forms under warm humid conditions, does not indicate that these conditions prevailed at the time of deposition (Reineck and Singh, 1980) only at the time that the clay mineral formed. As this stratum lies over the pallon at LP-1/23, it is possible that soil erosion in the immediate area provided the sediment. The almost impenetrable nature of the clay may have resulted from deep burial, with associated compaction, but this is probably inconsistent with the presence of less indurated clay at greater depth, as this would have been exposed to greater weight and should consequently have been more compacted. It seems probable that, following exposure, the surface hardened, rather as a kaoline-rich plinthite would harden to form a laterite (FitzPatrick, 1983). The presence of well humified, fine, herbaceous roots close to the top of the clay implies that this formed a vegetated surface, probably dating from the early Holocene, and possibly with the surface configuration illustrated in Figure 4.4a.

The north-south transect across the wider part of the marsh revealed a stiff sandy clay dipping northwards from LP-1/4. This may represent the same early Holocene vegetated surface, an hypothesis supported by the presence of clay granules towards the top of the clay at LP-1/6. These are, according to Reineck and Singh (1980), characteristic of the subaerial exposure of water-laid sediments.

The surface configuration illustrated in Figure 4.4a probably resulted, at least in part, from the erosion of the stiff clay during the high energy regime in which the overlying sands, clayey sands and gravelly sands were deposited. If the results of roundness analysis are considered (Table 4.2) it appears that the sand present in the clay (stratum 1) and the overlying sand (stratum 2) are almost identical in terms of roundness characteristics. It therefore seems possible that the clay was the sediment source for the overlying sand and that during the high energy phase most of the clay, silt and fine sand was removed leaving predominantly medium sand. This would require the erosion of a considerable depth and/or area of clay situated to the seaward and could have resulted from sea-level rise relative to the land in the early Holocene. In this case the transition between the indurated clay and the overlying sediment would mark the first Holocene transgressive overlap at this site.

The clayey, sand stratum which lies immediately below the peat contains a higher proportion of coarse sand and the sand is subangular rather than subrounded. This increased angularity could reflect the formation of an open barrier to the seaward; this part of the site having become a protected swash zone, rather than being in an open swash zone position. The hypothesis is supported by the diatom phase at the top of this stratum (LP-1/32a) which shows a declining marine influence. An impoverished diatom zone below this could result from the fact that valves are predominantly silt-sized and/or from frustules being fractured and abraded, then dissolved in marine coastal waters. Jones (1958) points out that dead micro-organisms must be considered as sedimentary particles, thus silt-sized valves are unlikely to be deposited in a high energy environment characterized by the deposition of medium sand. Diatom phase LP-1/32a, interpreted according to Ehrlich (1975), suggests that the water is oligohaline and that, at least the upper part of this sand was deposited in a lagoon completely isolated from the ocean by a closed barrier, or connected to it by a very distant tidal inlet. This sequence is indicative of a regressive overlap which must pre-date 7150 ± 120 BP, the age of the base of the peat.

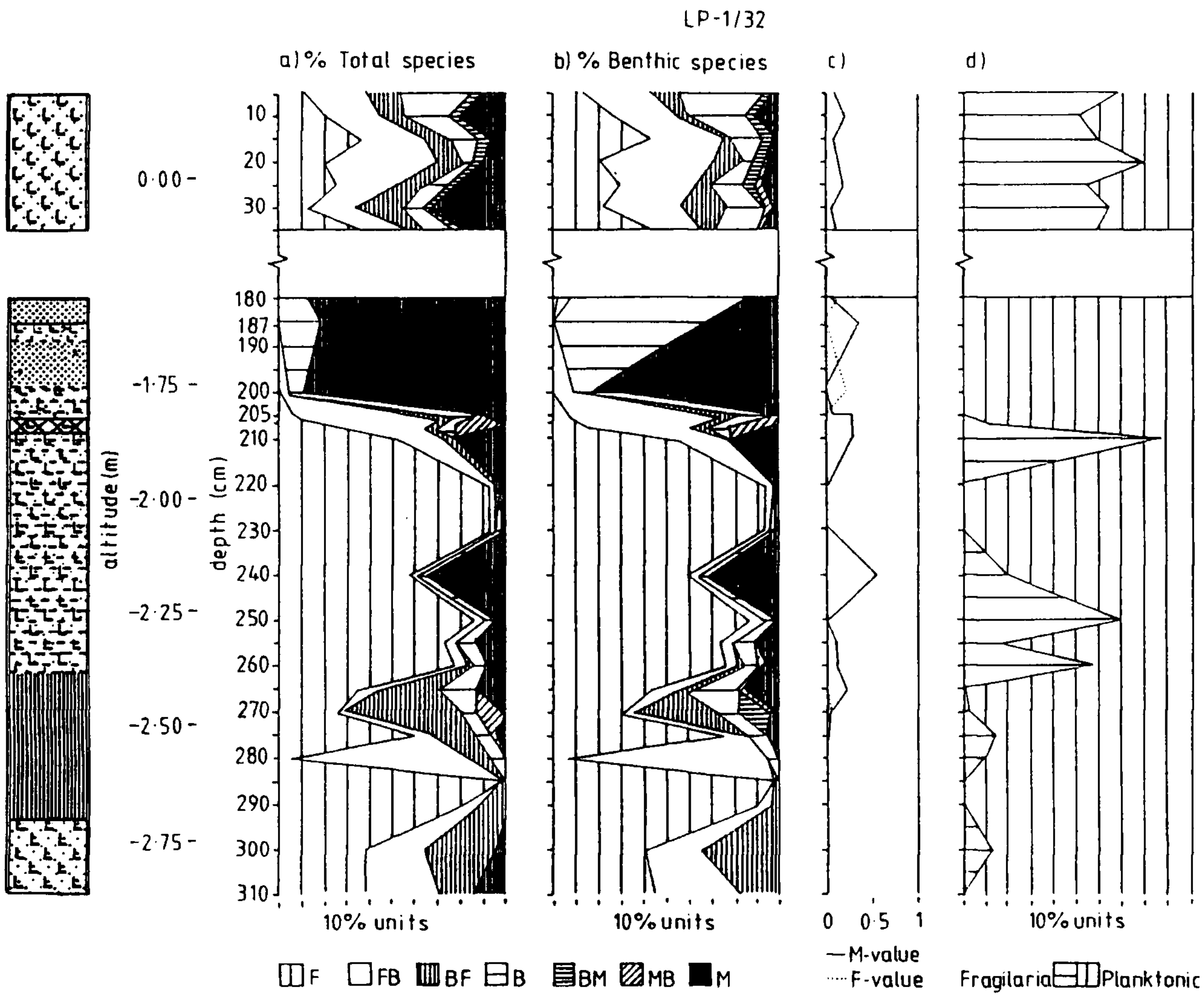


Figure 4.12 A diagram showing (a) the % total diatom species present, (b) the % benthic diatom species present, (c) fresh and marine allochthonous diatom groups expressed as ratios of the autochthonous group and (d) the *Fragilaria* - Planktonic representation in core LP-1/32

The peat either only accumulated in the linear depression, or was only preserved in this depression (Figure 4.4c). It is predominantly herbaceous, but with ligneous roots towards the periphery. At the base of the peat the diatom phase (LP-1/32b) suggests that the water providing the most suitable environment for peat accumulation was fresh (following Hedgepeth, 1953), indicating a further decline in marine influence. Towards the top of the peat, however, and in the fine detrital mud at borehole LP-1/31, there is a notable marine influence. At LP-1/32 the diatom succession through the peat as described in 4.3.1.4 and illustrated in Figure 4.12a, represents a transition from freshwater conditions at the base of the peat, through oligohaline to ∝ mesohaline, even approaching ß mesohaline at -2.47 m altitude. A comparison of Figure 4.12a and b indicates that this picture is created largely by benthic valves while Figure 4.12c suggests that the marine taxa are allochthonous, as are the fresh taxa at an altitude of -2.47 m. This suggests that the changes in water quality, implied by the diatom succession, actually occurred.

The increased salinity suggests that a tidal inlet had formed in the previously closed barrier system, either to the western end of Lagoa do Padre or possibly in the Lagoa de Guaratiba barrier. The woody roots in the peat, though they displayed no evidence of pneumatophites, may be of mangrove, in which case regular inundation is implied, or may represent more hydrophobic trees, in which case only periodic inundation is implied. Nevertheless it seems likely that the surface of the peat, at LP-1/32, lay between MSL-Ilha Fiscal and MHWS-Ilha Fiscal. This increased marine influence indicates a transgressive overlap, beginning at 6800 $\pm$ 110 BP.

The picture becomes somewhat complicated towards the top of the peat stratum, where diatom assemblages suggest decreasing marine influence, yet the organic clay, which lies over the peat, suggests a rising water level.

The diatom salinity phase implies that the tidal inlet in the barrier had closed, causing a return to oligohaline water. It is likely that the lagoonal water level lay between MSL-Ilha Fiscal and MHWS-Ilha Fiscal, as the modern tidal data discussed in 3.4 suggested a close relationship between water levels in closed lagoons and MSL. Therefore, the increasing water depth implies a relative rise in sea level and, despite the general lack of marine diatoms in the succession, a transgressive overlap. At both LP-1/31 and /32 evidence of the proximity of the ocean is provided in diatom salinity phases LP-1/31c and LP-1/32f and h. Figure 4.12b indicates that the marine diatoms are largely benthic, but Figure 4.12c suggests that they are allochthonous. It is not possible, from these data, to ascertain whether inlets existed, but if they did they were probably small and a considerable distance from Lagoa do Padre. Equally, there could have been no permanent inlet; the marine diatoms entering the lagoon during high tides when low points in the barrier were overwashed, or when fresh water built up in the lagoons to a similar level and discharged to the ocean through a short-lived inlet (Oliveira *et al.*, 1955a,b).

The sands present in the predominantly fine, clastic sediment deposited during this period are generally subangular (Table 4.2), which supports the hypothesis of a relatively closed lagoonal situation. The increased sand content in upper stratum 6 of LP-1/32 is unrelated to the rise in marine diatoms at LP-1/32f, so does not provide support for the presence of an inlet.

Salinity phases LP-1/31f and LP-1/32j indicate an abrupt change in water salinity, as these reflect polyhaline conditions. Interestingly LP-1/32j is noticably more marine influenced than LP-1/31f, despite the close proximity of the two boreholes. The change is, however, also accompanied by coarser sediment which extends to a lower altitude at LP-1/32. This implies that there may be an unconformable contact and the finer sediment deposited during the period marked by LP-1/31f was subsequently removed. The dominance of marine stenohaline *Paralia sulcata* var. *biseriata* Grun. towards the top of LP-1/32j indicates a transition from polyhaline to marine water.

This sequence suggests that the Lagoa do Padre barrier was breached. Present barrier morphology points to at least 1.3 km at the east of the lagoon being left intact, although the pattern of sedimentation which accompanied the breach indicates that much of the barrier was destroyed. A muddy clay with *Anomalocardia brasiliana* (Gmelin) shell fragments extends from the west, thinning to the east, and is overlaid by quartz sand with *A. brasiliana* (Gmelin), the surface of which dips from east to west. A comparison of the surface of the underlying muddy clay and the surface of this sand (Figure 4.4d and e) illustrates a clear change in the depositional environment. Also the sand is subangular which is suggestive of a protective swash zone.

The sand and gravelly sand with *A. brasiliana* (Gmelin) shell fragments which covers the lower stiff clay over the wider part of the site is assumed to have been deposited unconformably over the clay at this time.

The diatom-poor zone, which marks the shelly sand, probably resulted from the fact that diatom frustules are predominantly silt sized (Jones, 1958). The concentrations of *A. brasiliana* (Gmelin) fragments and single valves, could indicate continued polyhaline conditions, as this species inhabits open silty or sandy floored lagoons whose salinity is somewhat freshened by runoff (Fairbridge, 1976). This is, however, a tentative suggestion because the lack of entire shells indicates that *A. brasiliana* (Gmelin) was not *in situ*. Brito and Lemos (1982) stated that *A. brasiliana* (Gmelin) is the only living mollusc found in Lagoa de Araruama which, according to Rodrigues and

Boardman (1982), has a mean salinity of 55%. This is taken as evidence of the adaptability of the species.

The destruction of the barrier at the western end of Lagoa do Padre exposed Site 2 to marine influence. At this site another virtually impenetrable, sandy, clay stratum with woody and herbaceous roots is presumed to represent the early Holocene vegetated surface. Over this is a dark grey, sandy clay which is possibly related to the pre-breach rise in lagoonal water level from 6800 $\pm$ 110 BP. If true, this represents a transgressive overlap, as does the covering of gravelly sand which is assumed to represent the first post-breach marine sedimentation at this site. To the south, the fact that it is intercalated with a muddy clay suggests a period of quiet water sedimentation, which possibly implies, barrier formation immediately to the seaward. Nevertheless, this stratum is diatom poor and no dating has been attempted, so this interpretation must remain highly speculative.

The dark to very dark grey, muddy, clayey silt with *Anomalocardia brasiliana* (Gmelin) fragments, which covers the gravelly sand, contains countable concentrations of diatoms and is clearly marine in character (Figure 4.13a). If only the benthic population is considered (Figure 4.13b), the lower clay appears to be largely brackish and there is a possibility (Figure 4.13c) that the marine valves are allochthonous, while the upper clay is largely marine. This difference is, however, most likely to reflect changes in water depth. The brackish dominated part of the benthic succession is assumed to correspond to a period of deep-water sedimentation when the autochthonous population would be largely planktonic and the benthic population allochthonous. The marine dominated part of the benthic succession is believed to relate to a period of shallower water deposition where the benthic valves were autochthonous. The stratigraphic sequence clearly shows that the sediment is much more sandy when the salinity

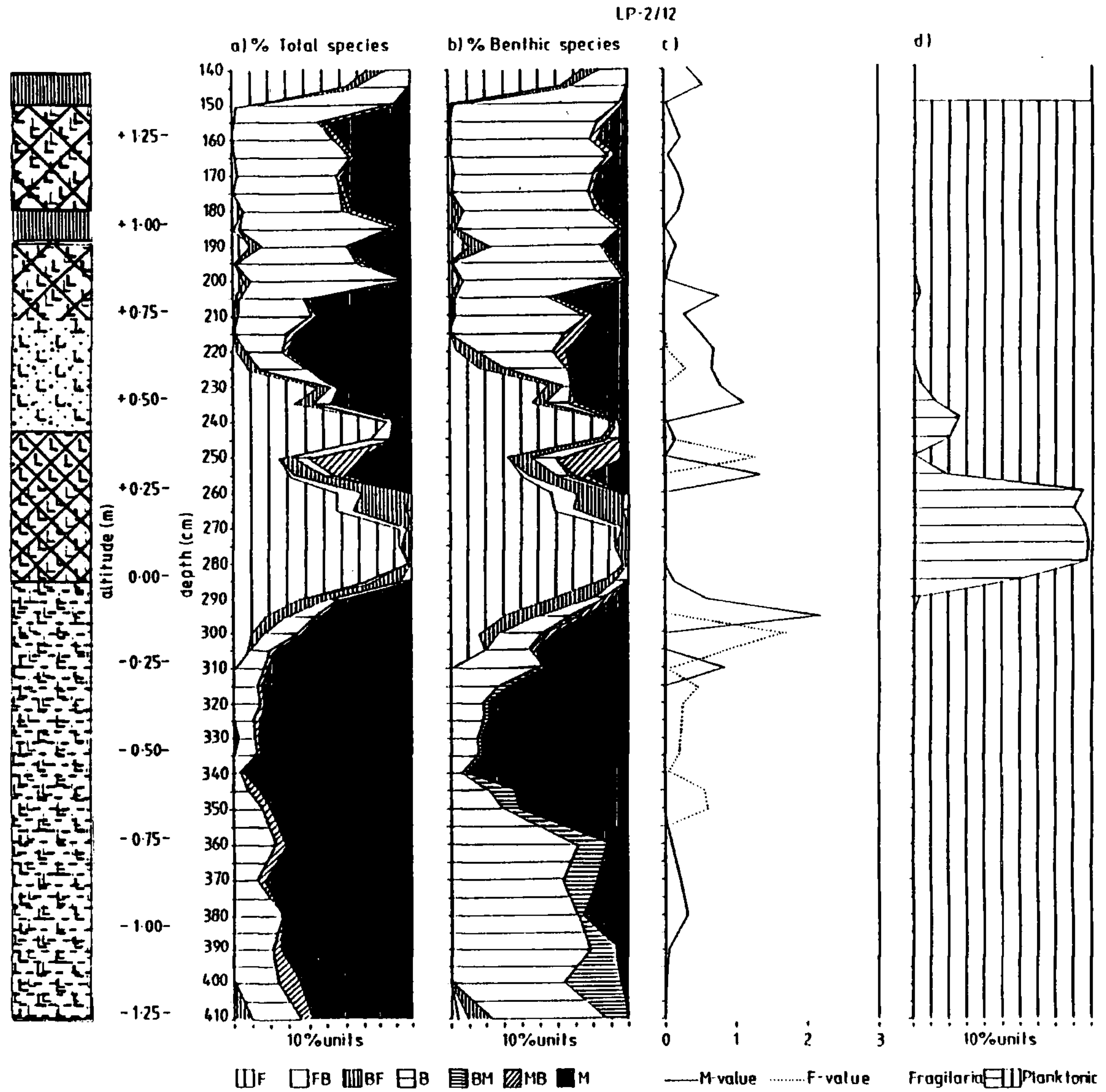


Figure 4.13 A diagram showing (a) the % total diatom species present, (b) the % benthic diatom species present, (c) fresh and marine allochthonous diatom groups expressed as ratios of the autochthonous group and (d) the *Fragilaria* - Planktonic representation in core LP-2/12

phases are dominated by marine, benthic valves, indicating shallow water. There thus appears to be a regressive overlap at -0.52 m altitude and a transgressive overlap at -0.37 m altitude. Unfortunately these cannot be dated.

At -0.22 m altitude fresh diatom valves begin to appear in significant numbers. Figure 4.13c indicates that between -0.22 and -0.12 m altitude the fresh valves are allochthonous, while above -0.12 m, the marine valves are allochthonous. This implies that -0.12 m altitude marks the beginning of the regressive overlap at LP-2/12. It is envisaged that a lower relative water level exposed the northern part of the site first, permitting the development of a fresh diatom flora which contaminated the death assemblage at LP-2/12. Later, after a further relative drop in water level a freshwater flora developed at LP-2/12, but marine diatoms were deposited over the area during high tides.

The polyhaline, clayey silt is overridden by sand at the seaward end of the site, which suggests that the decline in marine influence results from the formation of a sand barrier across the mouth of the Site 2 bay. To the landward, the diatom assemblage suggests that the water is oligohaline. In this shallow, quiet water situation a silty, clayey, fine detrital mud was deposited from *c.* 5230 $\pm$ 90 BP which marks the point of complete isolation from marine influence. This regressive overlap results from the protective affect of the barrier, but as the barrier is characteristic of progradation it would seem that this is not an extra-local event. Barriers formed across many similar embayments.

Towards the top of the fine detrital mud stratum there is a marked increase in marine and marine-brackish diatoms (LP-2/12e), many of which are benthic. Figure 4.13c suggests that at 0.28 m altitude the salt tolerant valves are allochthonous, whereas at 0.33 m they are autochthonous. This implies that the barrier was breached just prior to 4850 ± 80 BP and that polyhaline conditions prevailed. This biostratigraphic change is accompanied by a lithostratigraphic transition from silty, clayey mud to sandy mud at 0.24 m altitude. This transgressive overlap has not been dated, although material is available for dating.

The upper sandy mud and lower, overlying, clayey sand shows a return to oligohaline conditions (LP-2/12f), indicating a regressive overlap commencing at *c.* 4850 ± 80 BP.

At an altitude of 0.48 m (Figure 4.13) there is a notable presence of marine diatoms. Figure 4.13c indicates that these are allochthonous, but irrespective of this, the domination of brackish and marine diatoms is clearly indicative of polyhaline conditions.

The sediment fines at 0.71 m altitude from clayey sand to sandy, muddy clay indicating a reduction in the energy environment. This could result from increased protection from oceanic influence or from deepening water, although the associated reduction of marine diatom concentrations and slightly increased freshwater presence suggests the former. The water would seem to have become ß mesohaline representing an undated regressive overlap at 0.83 m altitude. The conclusion that this transition represents a regressive overlap is supported by the development of a thin peat stratum over the sandy, muddy clay.

Above the peat there is a slight increase in marine and a decline of fresh diatoms indicative of a return to polyhaline conditions, and a transgressive overlap. The thickness of this peat permitted only one ^{14}C age determination to be made : 2590 ± 65 BP. For interpretational reasons which will become clear later, this date will be taken as the age of the transgressive overlap.

The final polyhaline phase ends with peat formation at 2270 ± 55 BP. The diatom assemblage at the base of the peat indicates oligohaline water and displays increasing freshwater content. This marks the final regressive overlap at Site 2. It is not clear whether this retreat of marine influence was confined to Site 2 or occurred over the whole of what is now Lagoa do Padre. Muehe (1982) believed, on the basis of sea-level data from São Paulo State (Suguio and Martin, 1981), that the present Lagoa do Padre barrier formed at 2700 BP. The evidence presented here indicates that this is too old, but it may be of the right order, in other words *c.* 2300 BP. It is thus believed that this final regressive overlap at Site 2 marks the formation of the present Lagoa do Padre barrier.

At Lagoa do Padre Site 1 the transition from sand to clayey sand (-0.13 m altitude at LP-1/32) and LDSP LP-1/32h are assumed to relate to the final regressive overlap at Site 2 and to the isolation of the present lagoon from the ocean. Hence, this regressive overlap is also tentatively dated at *c.* 2300 BP.

The fact that four salinity phases have been identified, post isolation, at LP-1/32 (Figure 4.7) and three at LP-1/31 (Figure 4.8) indicates that this youngest barrier has, at least been subject to overwash. Consulting Figure 4.12a-c, however, reveals that the marine diatoms are likely to be allochthonous and that the water was essentially α mesohaline throughout the period of deposition of the clayey sand. This is equivalent to the present-day situation discussed in 3.2.1.

Thus, along this part of the coast at least three barriers have formed during the Holocene. Two formed in front of the present lagoon and at least one formed behind it. The first formed in front of the lagoon at around 7150 ± 120 BP. It was subsequently breached at an unknown date. Following the breach, barriers formed across bays behind the present lagoon, including the Site 2 bay. These barriers either formed in two stages with an intervening breach or two distinct barriers formed, the younger merging with the remnants of the older. The first stage of formation has been dated at 5230 ± 90 BP. The present day Lagoa do Padre barrier is believed to have formed at approximately 2300 BP. The high *Fragilaria* Lyn. percentages shown in Figures 4.14d and 4.15d, following the proposed periods of barrier formation, indicative of reduced marine influence as discussed in 3.2.4, add weight to this theory. These phases with high *Fragilaia* Lyn. percentages suggest closed barriers.

4.4 Lagoa de Guaratiba

Lagoa de Guaratiba interconnects with Lagoa do Padre in the east and Lagoa de Barra in the west. It is the third largest lagoon in the Maricá System with an area of 6.2 km^2. Unlike Lagoa do Padre which is elongated in an east-west direction, parallel to the present coastline, Lagoa de Guaratiba is elongated in a northeast-southwest direction.

It is surrounded by a series of headlands, many with vertical cliffs and sediment-filled bays which are separated from the present lagoon by barriers. The lagoon is isolated from the Atlantic by an approximately 1 km long single barrier which lies between the settlement of Guaratiba, adjacent to the 13 m high Ponte Preta, and the village of Barra, adjacent to the 48 m high Ponta Fundão. According to Muehe (1982) the barrier is 6 m high. At its western end, however, is the 'Barra da Emergencia', a *lido* which is approximately 4 m high, but was lower until recent human interference which permitted a road to pass along this barrier. The *restinga* vegetation is poorly developed.

4.4.1 Presentation of results for Lagoa de Guaratiba Site 1

Lagoa de Guaratiba Site 1 is situated in an embayment on the eastern side of the lagoon. It lies directly north of Lagoa do Padre Site 2 (Figure 4.1). The bay is cut off from the lagoon by a barrier, but still contains shallow water (approximately 30 cm). Only stratigraphic analysis has been carried out at this site, although borehole LG-1/6 is held in cold storage in Durham making further investigation possible. Six boreholes have been sampled at this site (Figure 4.14).

4.4.1.1 Stratigraphic analysis

At the base of the most landward borehole (LG-1/1) is a light grey, sandy clay which, from an altitude of -4.52 m is overlaid by 4.25 m of gravel and sand (Figure 4.15). These are covered by a very dark grey, muddy clay. At boreholes LG-1/3 and /6, 40 m lagoonward, the most complex stratigraphic sequence was recorded. Gravelly sand strata intercalate sandy, muddy clay and clayey, fine detrital mud strata. The clayey mud which is found at -3.80 m altitude at LG-1/3 can be traced through LG-1/2 to LG-1/4 where it is at -5.65 m altitude. The stratum dips at an angle of 1° to NW. Grey, sandy, muddy clay extends from the base of the LG-1/2 sequence to -0.37 m altitude and from the base of the LG-1/4 column to -0.32 m. At LG-1/5, the most lagoonward borehole, the grey, sandy, muddy clay extends from the base of the sequence to -0.29 m, but is interrupted by 1.95 m of gravel and sand between -0.65 m and -2.6 m altitude. Thin clay and detrital mud strata cover the dark grey to very dark grey, sandy, muddy clay over the whole site and

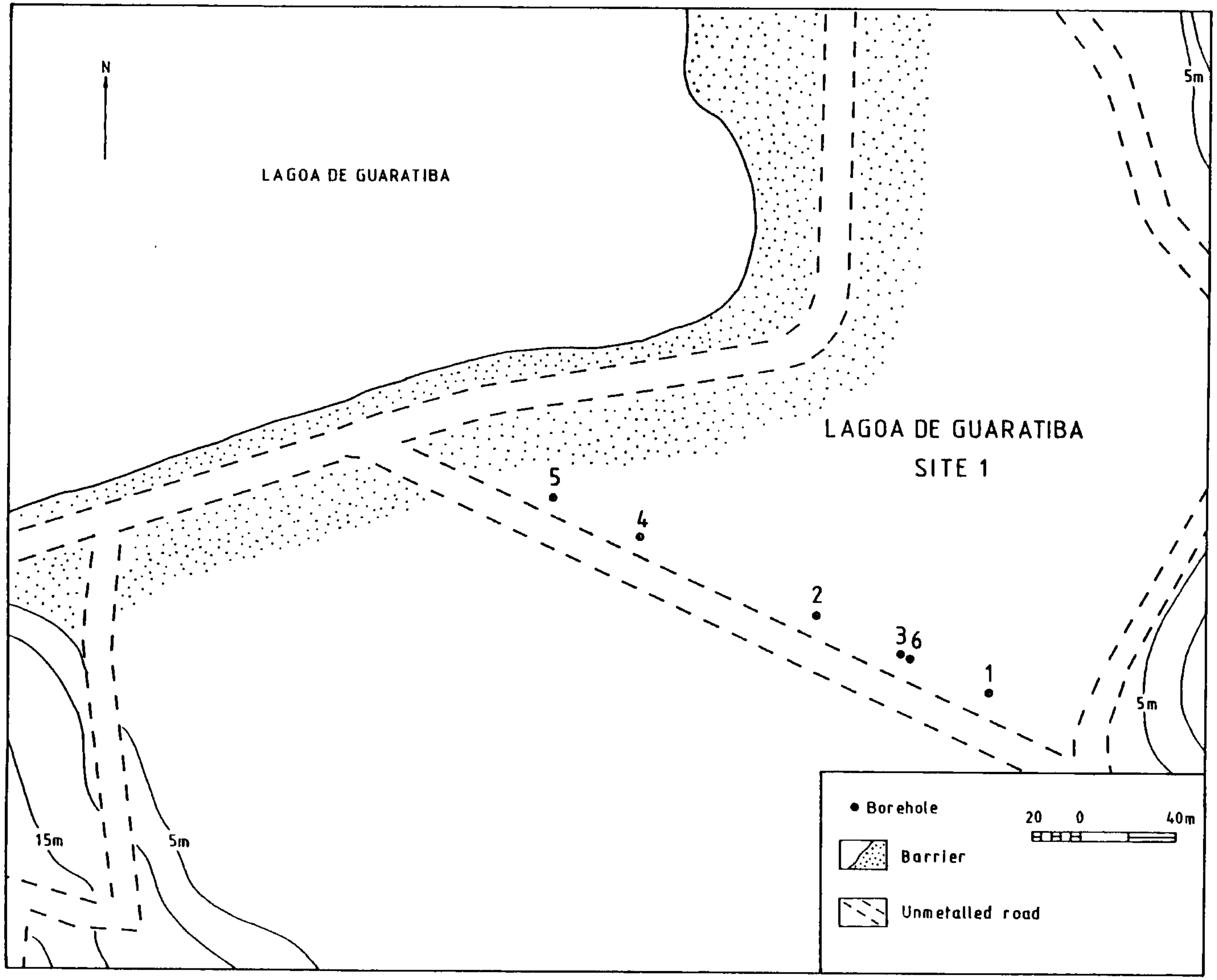


Figure 4.14 A map of Lagoa de Guaratiba Site 1 showing the location of boreholes

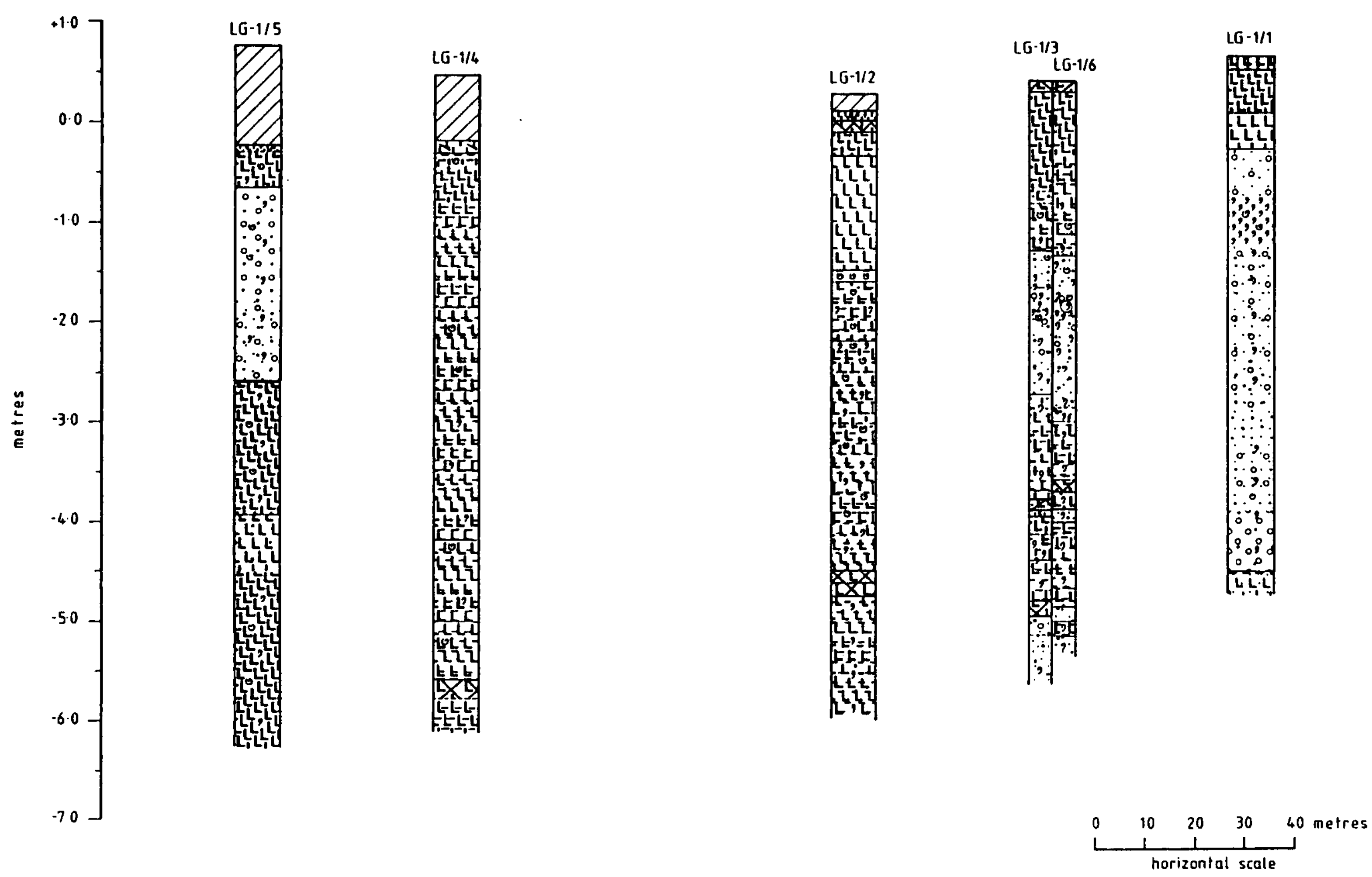


Figure 4.15 A diagram showing the stratigraphy of Lagoa de Guaratiba Site 1

between LG-1/2 and LG-1/5 there is also a thin herbaceous peat stratum thickening from 2 cm at LG-1/5 to 5 cm at LG-1/2.

It is possible to draw a distinction between sediment containing shells, particularly *Anomalocardia brasiliana* (Gmelin) and a small conical gastropod, and deposits which are shell-free. At LG-1/1 the considerable depth of gravelly sand and sandy fine gravel contains shells between -0.7 and -4.52 m altitude. The intercalated muddy clay and gravelly sand contain shells below -0.76 m at LG-1/6 and at LG-1/3 below -0.83 m altitude. At LG-1/2 the muddy clay is shelly below -1.55 m and at LG-1/4 they are found between -0.32 and -0.43 m, then between -1.83 and -5.65 m altitude. Virtually the entire LG-1/5 core below -0.29 m contains shells.

4.4.2 Interpretation of the stratigraphy at Lagoa de Guaratiba Site 1

This site lies at a similar altitude to Lagoa do Padre Site 1, yet, despite boring to depths of over 7 m, there is no evidence of an early Holocene vegetated surface. It must be assumed that the equivalent surface was at a markedly lower altitude or has been eroded in this embayment.

In the absence of diatom analytical evidence, the presence of *Anomalocardia brasiliana* (Gmelin) will be used as an indicator of polyhaline water conditions. Thus, from the description of its distribution above, it would appear that most of the sediment at this site was deposited in polyhaline water.

The sand and gravel close to the scarp are presumed to represent a relatively high energy beach situation, while the predominantly clayey deposits away from the scarp are presumed to have settled in quieter, deeper water. The detrital mud stratum which slopes at 1° towards the lagoon and lies between shelly clay is assumed to have been deposited in a less saline regime. This would therefore mark a regressive overlap. Above this there is a clear resumption of polyhaline conditions and a transgressive overlap.

At -2.6 m altitude in borehole LG-1/5 the clay is overlaid by gravelly sand which is the landward extension of the barrier that now separates the site from the lagoon. To the landward this regressive overlap can be traced between boreholes by assuming that above this transition no *A. brasiliana* (Gmelin) would be found. The water environment would have been less saline, protected from marine influence by the barrier. Boreholes LG-1/4 and /5 do, however, through the presence of *A. brasiliana* (Gmelin) after the barrier had formed, suggest that the barrier was breached for a period, before final isolation.

While dates cannot be attributed to these events, it is interesting to note that a broadly similar pattern of late Holocene barrier evolution to that recorded at Lagoa do Padre is indicated here: that is, the formation of barriers across embayments around the present-day lagoon followed by the formation of the present day barrier which separates the lagoon from the Atlantic.

4.5 Itaipu-Açu

Itaipu-Açu is a sandy coastal plain stretching from the Serra da Tiririca in the west to Lagoa de Marciá in the east. The plain is fronted by two barriers, an inner fossil barrier and an outer present-day barrier. The crest of the former is 4.8 m higher than that of the present barrier which reaches an altitude of 7.4 m (Muehe, 1982). These barriers are separated by the Canal da Costa, an approximately 12.5 km long channel which opens to the ocean at the western end of the plain, below the Falso Pão de Açucar. 2 km from its western end a large stream, the Rio Itocáia enters the canal, while in the east, the channel joins the Rio Brejo da Costa which connects it with the Maricá Lagoonal System. Two small inselbergs, the Morro do Céu and the

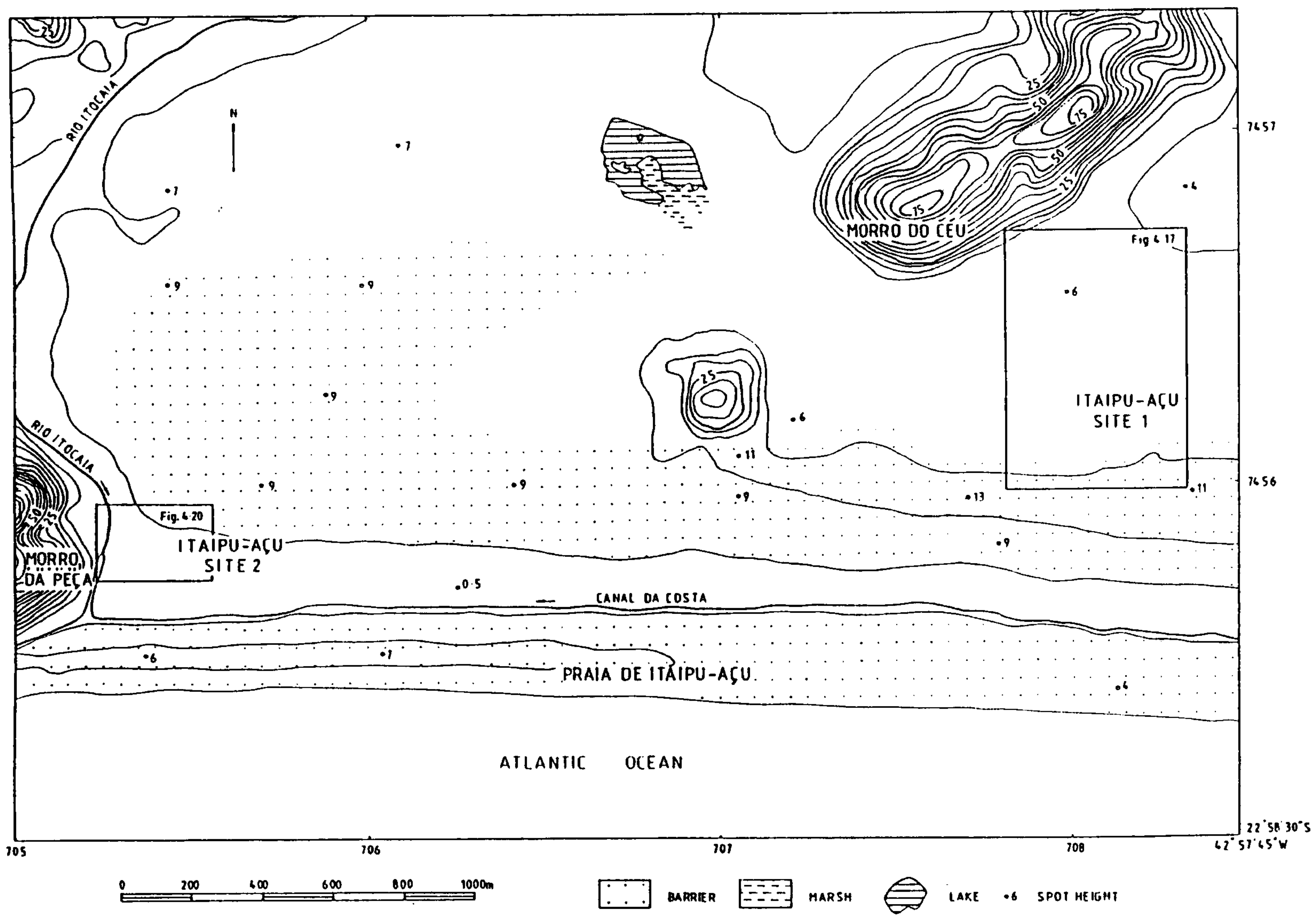


Figure 4.16 A map of western Itaipu-Açu showing the location of sampling sites

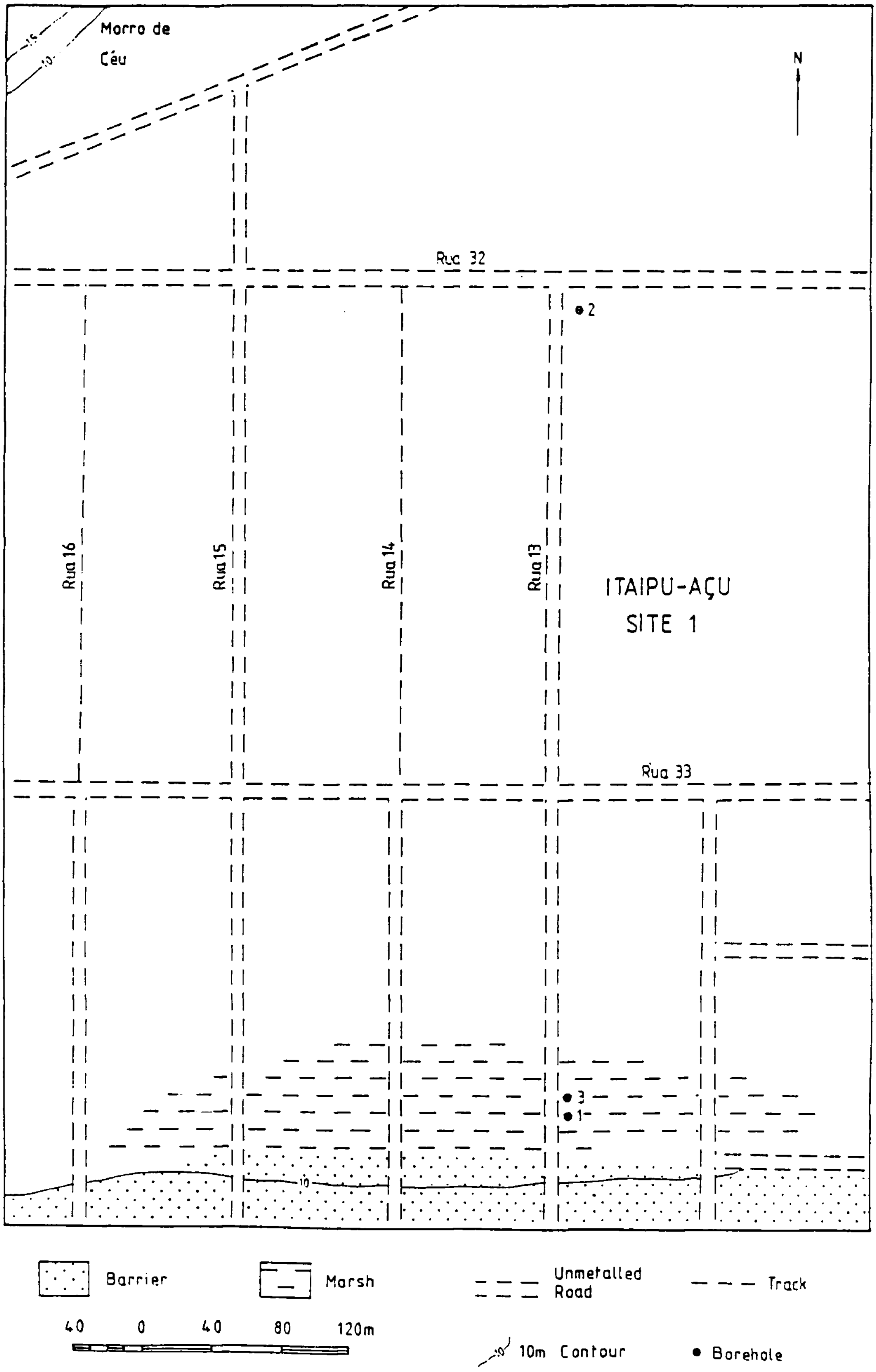


Figure 4.17 A map of Itaipu-Açu Site 1 showing the location of boreholes

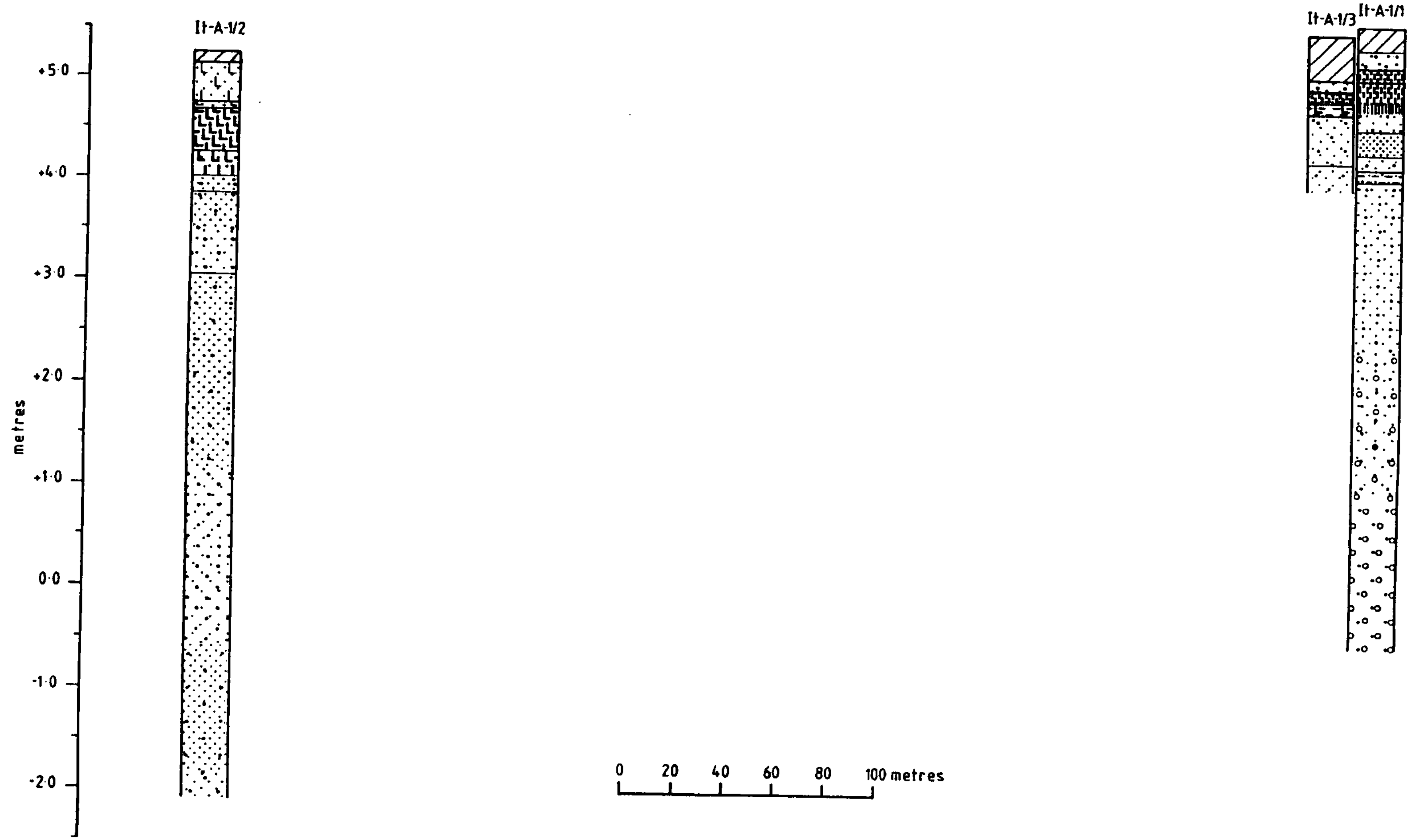


Figure 4.18 A diagram showing the stratigraphy of Itaipu-Açu Site 1

Morro da Peça, interrupt the plain in the west, rising to approximately 75 m. There is no lagoon behind the fossil barrier, but there are some marshy areas. The quartz sand which forms the beach at Itaipu-Açu is coarser than beach sand elsewhere along this part of the Rio de Janeiro coast (Muehe, 1979).

4.5.1 Presentation of results for Itaipu-Açu Site 1.

Itaipu-Açu Site 1 lies between the fossil barrier and the Morro do Céu (Figure 4.16).

4.5.1.1 Stratigraphic analysis

Only three boreholes have been sampled at this site (Figure 4.17). Nevertheless, the analysis indicated that the stratigraphic sequence is dominated by a gravelly sand, predominantly rounded to well-rounded quartz, to a depth of over 7 m (Figure 4.18). Within 1.2 m of the surface (above 4 m altitude) the sand is intercalated with fine grained inorganic and organic rich strata.

At the most seaward borehole (It-A-1/1) in excess of 4.5 m of sand is overlaid, above 4.11 m altitude, by a 14 cm thick black stratum with equal parts of humified organic matter and sand. Then above 4.80 m altitude there is a 40 cm thick horizon of dark reddish brown to black, herbaceous peat. 10 m to the north at It-A-1/3, above 4.82 m altitude is a 10 cm thick, black organic clay overlaid by 9 cm of very dark brown, well humified, herbaceous peat. At the foot of Morro do Céu (It-A-1/2) the sand is intercalated with a 61 cm thick stratum of mottled light and dark grey, sandy, kaolinitic clay.

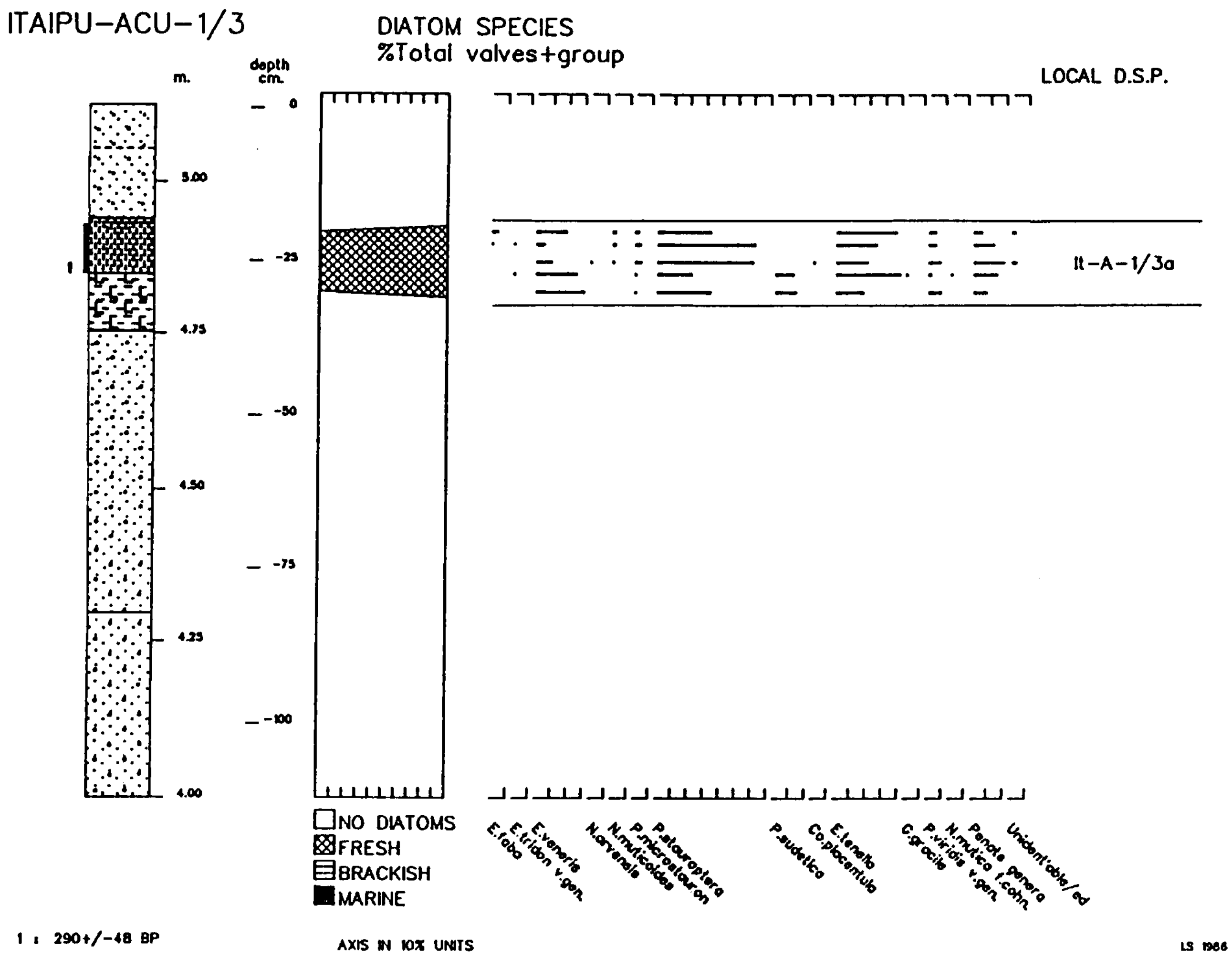


Figure 4.19 A diatom diagram for core It-A-1/3

4.5.1.2 Particle size analysis

The results of particle size analysis in core It-A-1/3 are presented in Appendix III together with a detailed stratigraphic description. All strata tested proved to have been accurately described in the field.

4.5.1.3 Diatom analysis

Countable concentrations of diatoms occur only between 4.84 and 4.95 m altitude at It-A-1/3. This succession, dominated by *Pinnularia stauroptera* var. *minuta* May., with *Eunotia veneris* (Kütz.) O. Müll. and *E. tenella* (Grun.) Hust., corresponds to a single fresh diatom salinity phase, It-A-1/3a (Figure 4.19). While not in countable concentrations, diatom species enumerated in It-A-1/3a are encountered to an altitude of 4.27 m.

4.5.2 Presentation of results for Itaipu-Açu Site 2

Itaipu-Açu Site 2 is situated between barriers, immediately to the east of the Morro da Peça, in the angle of confluence between the Rio Itacáia and the Canal da Costa (Figure 4.16).

4.5.2.1 Stratigraphic analysis

There are 12 boreholes at this site (Figure 4.20), eight of which are on a single north-south transect (Figure 4.21). The sampling interval varies from 5 to 40 m. Figure 4.22 shows the sedimentary relationship between this north-south transect and the adjacent boreholes.

The base of the sequence is dominated by gravelly sand which is composed mostly of quartz. A distinction can, however, be drawn between sand and gravel which contains felspar and that which does not. The sediment containing felspar is consistently found at the base of the sequence and

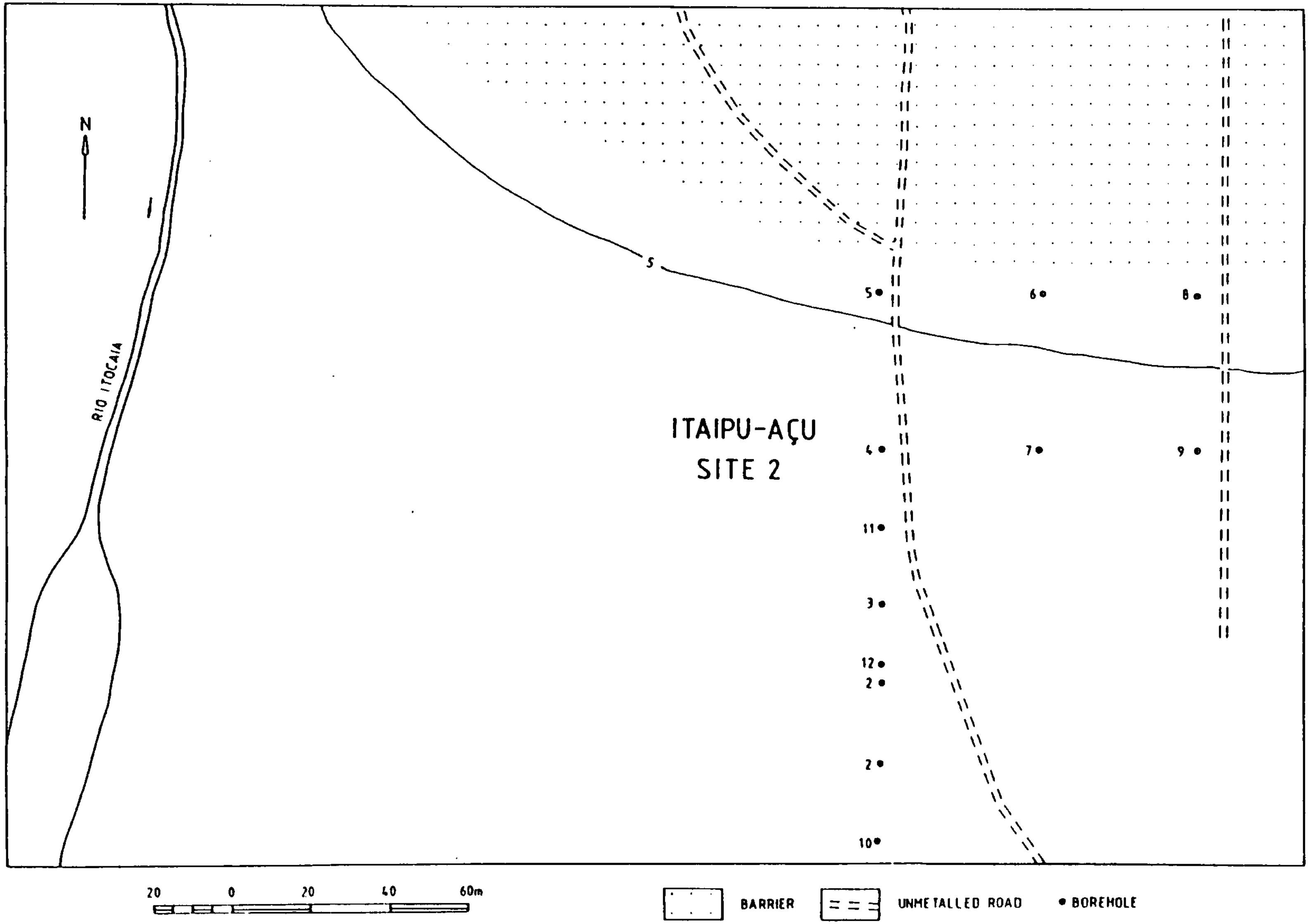


Figure 4.20 A map of Itaipu-Açu Site 2 showing the location of boreholes

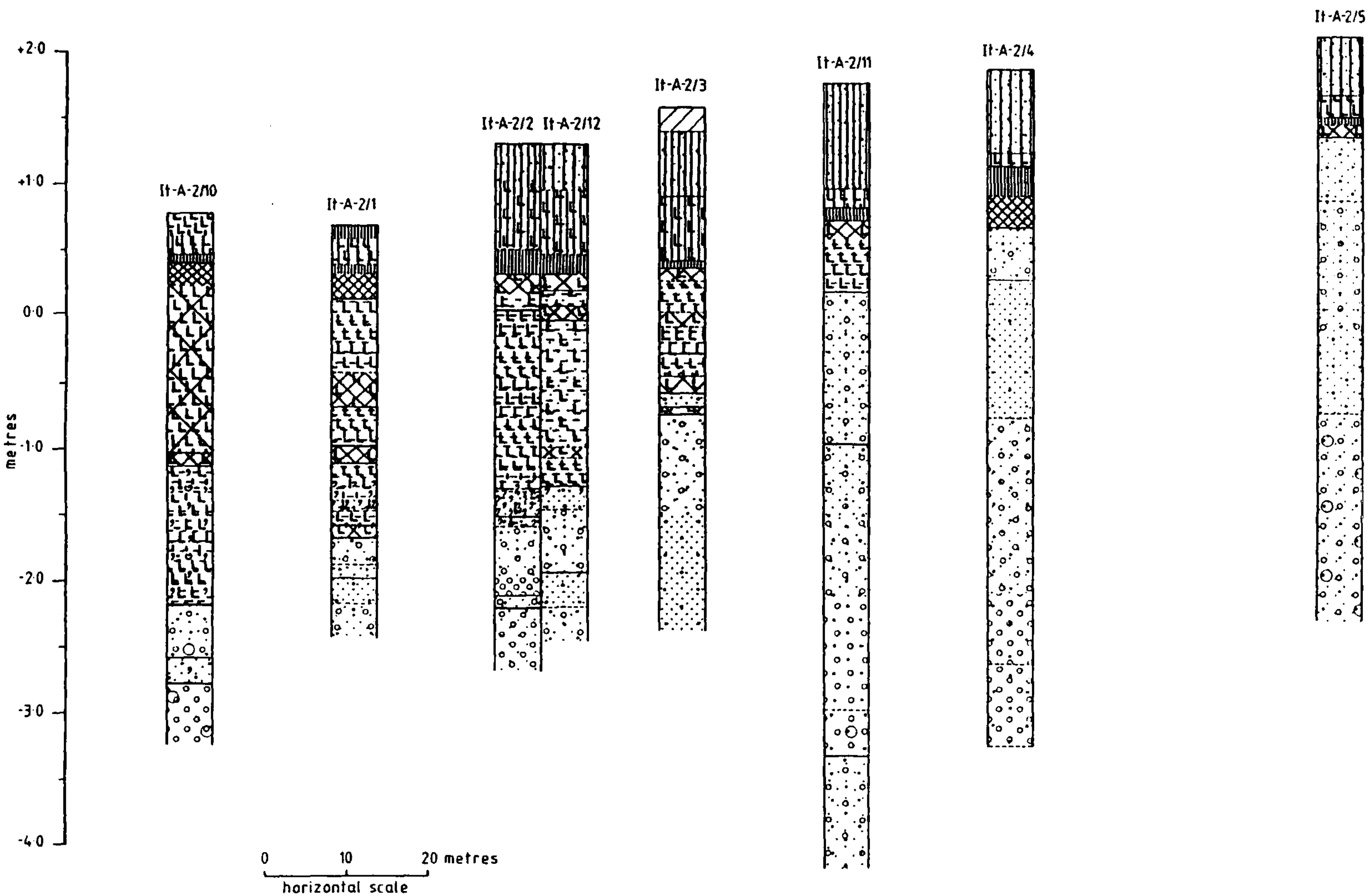


Figure 4.21 A diagram showing the stratigraphy of the main north-south transect at Itaipu-Açu Site 2

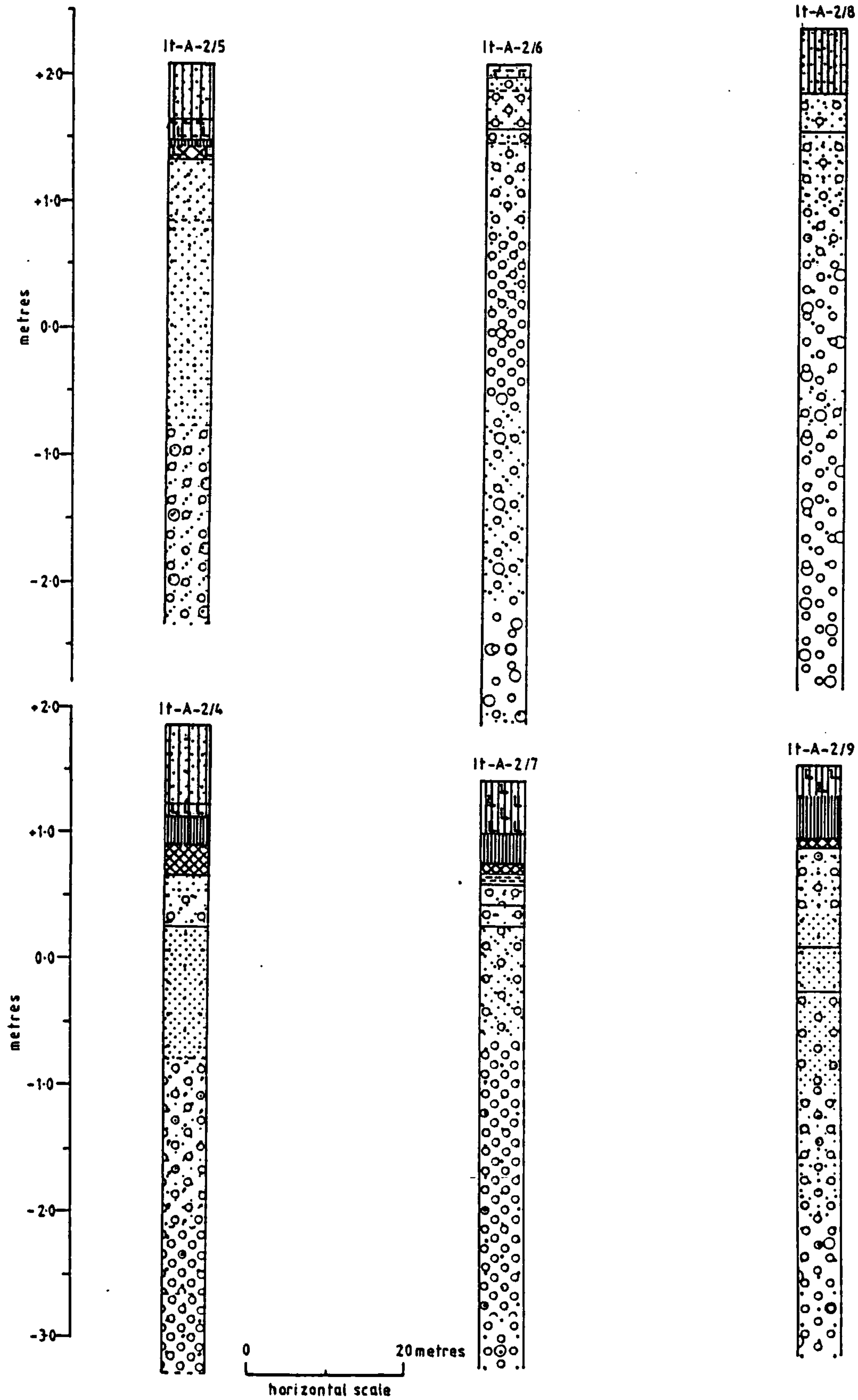


Figure 4.22 A diagram showing the stratigraphy of the east-west transects at Itaipu-Açu Site 2

ranges from sand with a trace of gravel to fine and medium gravel with a trace of sand. South from It-A-2/11 at 0.15 m altitude its surface dips seaward, initially at an angle of 5° then flattens to an angle of 1.4° until reaching -2.81 m altitude at It-A-2/10. North from It-A-2/11 the sand and gravel with felspar forms an undulating surface ranging from -0.79 to +0.94 m altitude, and can appear very close to the surface (47 cm depth). At It-A-2/10 the sediment is impenetrable below -3.26 m altitude and at adjacent It-A-2/1 there is a virtually impenetrable dark brown, gravelly sand below -2.43 m altitude.

A gravelly sand of quartz which dips seaward at an angle of 1.5° covers the lower sand over most of the site. South of It-A-2/3 it contains single valves and fragments of *Anomalocardia brasiliana* (Gmelin) (at It-A-2/10, /2 and /12) and is overlaid by a dark grey, sandy, muddy clay also containing *A. brasiliana* (Gmelin) valves and fragments. There are also shells and shell fragments of a small conical gastropod at It-A-2/10.

A stratum of very dark greyish brown, clayey, fine detrital mud can be traced from It-A-2/3 to It-A-2/10 overlying the wedge of shelly clay. This layer dips, almost imperceptibly seaward at an angle of 0.4°. Over it and extending as far landward as It-A-2/4 is a predominantly dark grey, sandy, muddy clay, intercalated with more organic rich strata.

The stratum which covers this is a very dark greyish brown, clayey, fine detrital mud with variable sand content which extends over most of the site. Only It-A-2/6 and /8 do not include this deposit. It ranges in thickness from 2 cm at its most landward to 23 cm at It-A-2/1 and dips gradually seaward. This area is then covered by the overlying very dark brown, well humified, herbaceous peat which varies in thickness between 4 cm at It-A-2/1 and 38 cm at It-A-2/9. Whereas the fine detrital mud thins towards the land, the peat is at its greatest recorded thickness at borehole It-A-2/4, /7 and /9 before thinning at It-A-2/5 and disappearing at It-A-2/6 and /8. The peat is covered by a very dark brown, peaty clay which is, in turn, overlaid by a peaty sand along the north-south transect between It-A-2/2 and /5.

4.5.2.2 Particle size analysis

Particle size analysis was carried out on core It-A-2/12. The results are presented in tabular form in Appendix III together with the detailed stratigraphic description. The coarse grained strata were accurately assessed in the field, but between stratum 6 and 11, the proportion of clay present was over estimated at the expense of silt. The changes should apply to boreholes south of It-A-2/4 where this dark grey, sandy, muddy clay intercalated with more organic rich strata, was recorded. The individual strata cannot, however, be traced with confidence from borehole to borehole, so this should be regarded as a sandy, muddy silt.

The detailed changes required at It-A-2/12 are listed below:

stratum 6		As3 → Ag2, As1
stratum 7		As2 → Ag1, As1
stratum 8	(1.34 to 1.57m depth) :-	As2, Ga1 → Ag3, As + Ga+
	(1.57 to 2.31m depth) :-	As2, Ga1 → Ga2, Ag1, As+
stratum 9		As1,Ga +→Ga1, Ag+ ,As+
stratum 10		As2 → Ag2, As+
stratum 11		As1 → Ag1, As+

4.5.2.3 Diatom analysis

Diatom analysis of core It-A-2/12 revealed 10 salinity phases (Figure 4.23). Below -1.37 m altitude there is an impoverished zone. It-A-2/12a extends from the top of stratum 5, a gravelly sand with *Anomalocardia brasiliana* (Gmelin) valves and fragments, to approximately the middle of overlying

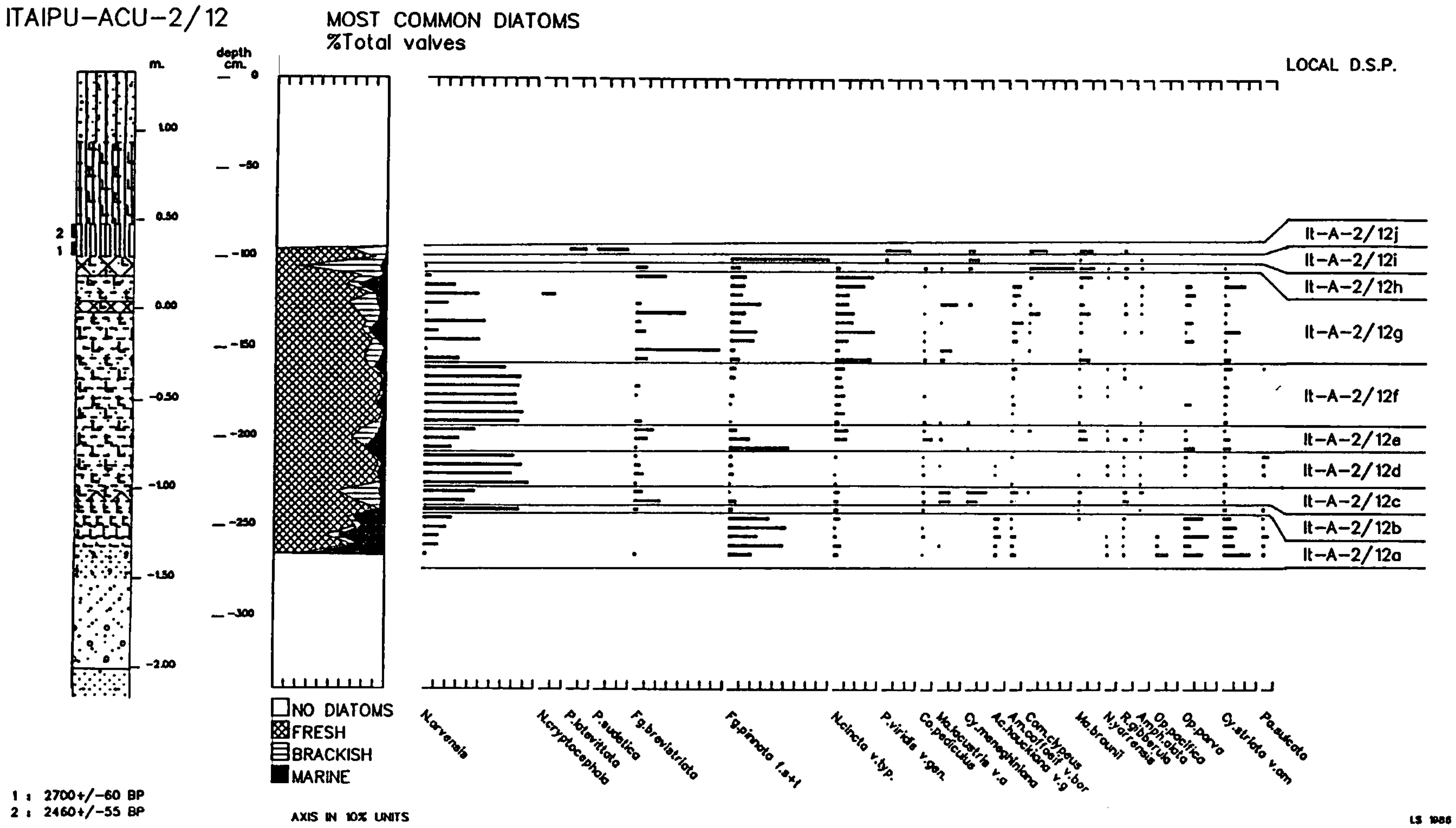


Figure 4.23 A diatom diagram showing the most common diatoms enumerated in core It-A-2/12 (see Appendix IV for the rare diatoms)

muddy, clayey silt stratum. The phase is characterized by a fluctuating, but gradually declining, marine count - though it is predominantly fresh-brackish; dominated by *Fragilaria pinnata* f. *subrotunda* May.. *Opephora parva* (V.H.) Krasske and *Cyclotella striata* var. *americana* A.Cl. are the most common marine diatoms.

It-A-2/12b, which marks upper stratum 6, is a narrow fresh phase heavily dominated by *Navicula arvensis* Hust.. Above this, It-A-2/12c is a fresh and brackish phase characterized by a rise in the number of brackish-fresh valves (both benthic and planktonic); notably *Mastogloia lacustris* var. *antiqua* (Schum.) A.Cl. and *Cyclotella meneghiniana* Kütz.. Fresh diatoms, however, particularly *N.arvensis* Hust., dominate. This phase extends from the clayey, silty mud of stratum 7 into the base of stratum 8.

It-A-2/12d and 12f are both fresh phases heavily dominated by *N. arvensis* Hust.. Between them It-A-2/12e is characterized by a relative fall in fresh and rise in fresh-brackish diatom percentages, accompanied by a slight increase in brackish and marine counts. The most common fresh-brackish diatoms are *Fragilara pinnata* f. *subrotunda* May., *F. brevistriata* Grun. and *N. cincta* Ehr.. These three phases mark the lower part of stratum 8 (below 1.57 m depth), differentiated by particle size analysis, which is a muddy, silty sand.

It-A-2/12g is a fresh phase in which fresh periods dominated by *N. arvensis* Hust. alternate with fresh-brackish periods dominated by *N. cincta* Ehr., *F. brevistriata* Grun. or *F. pinnatra* f. *subrotunda* May.. This phase ranges from upper stratum 8 to the base of stratum 11, the very dark, greyish brown, sandy, silty, fine detrital mud which covers most of the site.

It-A-2/12h is a predominantly brackish phase, dominated by *Campylodiscus clypeus* Ehr. with *Mastogloia braunii* Grun.. This marks the middle of stratum 11, while the top of the stratum is represented by It-A-2/12i which is fresh-brackish and dominated by *F. pinnata* f. *subrotunda* May..

It-A-2/12j, which marks the base of the herbaceous peat, is essentially fresh; dominated by *Pinnularia* Ehr. species, notably *P. sudetica* Hils. and *P. latevittata* Cl., although fresh-brackish *P. viridis* (Nitz.) Ehr. is also very common. The most notable brackish diatoms are *M. braunii* Grun. and *C. clypeus* Ehr. which together form 25% of the assemblage.

4.5.3 The sedimentary history of Itaipu-Açu

Muehe (1982), proposed that the fossil barrier formed at 5100 BP and that the present-day barrier formed at 2700 BP, based upon the sea-level curve of Suguio and Martin (1981). It was assumed that the fossil barrier had enclosed a lagoon similar in character to that at Maricá and that, during the late Holocene this had filled with lagoonal sediment. The sedimentary, diatom and radiocarbon evidence contradict this view.

The sedimentary sequence at Site 1, with well rounded quartz sand and gravel, similar to that composing the present Itaipu-Açu beach, is indicative of marine sedimentation. The fine grained sediment and organic deposits are at a considerable altitude above MSL (higher than 4 m) and the diatom succession clearly indicates that they accumulated in fresh water. The radiocarbon date on the peat of 250 $\pm$ 48 BP (in the period AD1500 to 1800) indicates that the freshwater phase is a recent phenomenon. It could relate to eighteenth century clearance of the lowland forest for sugar cane production; an hypothesis which is supported by the presence of charcoal in the black organic clay between 4.86 and 4.82 m altitude at It-A-1/3.

On the seaward side of the fossil barrier at Site 2, the gravelly sand containing felspar, while essentially marine in character, is assumed to have been influenced and possibly reworked by the neighbouring Rio Itocáia. The presence at It-A-2/1 of the almost inpenetrable dark brown gravelly sand 25 cm below the felspathic sand and gravel surface and a hard platy, dark brown sand and gravel 79 cm below the felspathic sand surface at It-A-2/4 suggests that this sand has been exposed to the atmosphere for a considerable time during which a soil profile has developed. The impenetrable layer representing an illuvial horizon, predominantly of iron oxide. An impenetrable layer discovered at It-A-2/10 could also be an iron pan.

The overlying gravelly sand which covers most of the site south of It-A-2/3 is assumed to represent the first Holocene transgressive overlap at this site. The presence of *Anomalocardia brasiliana* (Gmelin) shells towards the top of the sand at It-A-2/2 and /12, and through most of the sand at It-A-2/10 is indicative of a regressive overlap; the site presumably being protected from direct marine influence by the formation of a barrier which permitted freshwater runoff to freshen the oceanic waters making them polyhaline. The wedge of dark grey, sandy, muddy clay, with *A. brasiliana* (Gmelin) valves and fragments, which covers the sand supports this hypothesis, indicating a transition from a relatively high to a relatively low energy environment. In addition, the diatom succession (Figure 4.24a) at It-A-2/12a, which marks the transition from sand with *A. brasiliana* (Gmelin) to shell-free, muddy clay, shows a decline in marine diatoms. Figure 4.24c suggests that the fresh diatoms within the sand, are allochthonous but that they form the authochthonous component at the surface of the sand and in the overlying clay. Neverthless there is a clear marine influence until LDSP It-A-2/12b which is indicative of fresh water. Above this approximately 1.3 m of sediment has accumulated in an essentially fresh to oligohaline lagoon

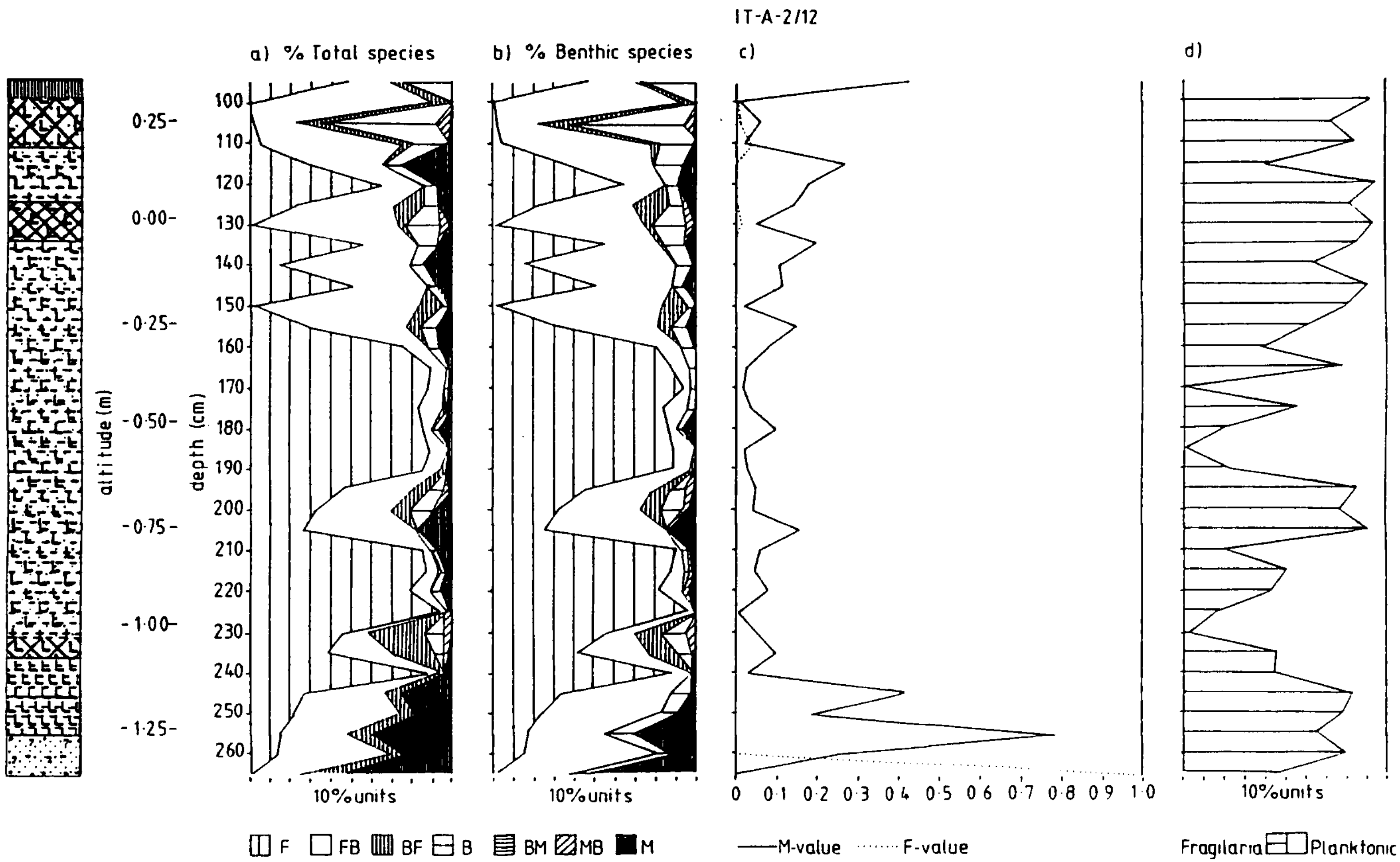


Figure 4.24 A diagram showing (a) the % total diatom species present, (b) the % benthic diatom species present, (c) fresh and marine allochthonous diatom groups expressed as ratios of the autochthonous group and (d) the *Fragilaria* - Planktonic representation in core It-A-2/12

in which, according to Figure 4.24c marine diatoms are allochthonous. There is evidence, however, particularly in the diatom succession, to suggest that the position of the sea level, relative to the site, has fluctuated during this period.

Immediately above the fresh assemblage of It-A-2/12b there is an increase in fresh-brackish, brackish-fresh and brackish diatoms, but not in marine valves. This is associated with a change from clay to mud deposition which is believed to result from a relative lowering of the water level. In these circumstances the increased salinity would probably result from evaporation. The sediment overlying the mud has deposited in fresh water (It-A-2/12d), indicating a rising water level and a transgressive overlap at -1.02 m altitude. At -0.77 m altitude there is a notable increase in marine diatoms and (It-A-2/12e) an increase particularly in fresh-brackish diatoms. This suggests that there was a relatively small, and probably distant tidal inlet in the barrier at this time. Above -0.67 m a freshwater regime is clearly indicated with much decreased marine influence. This (It-A-2/12f) is interpreted as a regressive overlap and is associated with sedimentation in a lower energy environment. Above this, to an altitude of 0.19 m, the diatoms are predominantly fresh-brackish with relatively consistent brackish and marine levels, although there are periods when fresh diatoms dominate. This phase is considered to reflect the presence of a small inlet and its base, at -0.32 m altitude, to mark a transgressive overlap. The periods of fresh domination indicate that these may be regressive overlaps, but the evidence does not allow these to be identified with sufficient confidence. It-A-2/12h which is dominated by brackish diatoms, notably *Campylodiscus clypeus* Ehr. and *Mastogloia braunii* Grun., would appear not to be related to a marine incursion as only approximately 2% of the assemblage is marine. This sandy, silty, mud stratum which lies directly under the peat is likely to have been deposited in relatively shallow water made α to β mesohaline by evaporation. It is thus interpreted as a regressive overlap which began shortly before 2700 ± 60 BP, the date from the base of the peat, which is when Muehe (1982) suggested the present barrier formed. Peat growth terminated at 2460 ± 55 BP at It-A-2/12 when it was overlaid by silty clay, marking a transgressive overlap. No diatoms are present in this sediment. The transgressive overlap must have been followed by a regressive overlap as the site is now dry.

While it is clear that the present barrier is older than 2700 BP, the age estimates used in the following section are speculative, although they seem the most probable when all the evidence from this and other sites is considered. It is suggested that the fossil barrier and the sedimentary sequences behind it are Pleistocene in age, with only the surface sediment on the face of the barrier being reworked during the Holocene. This formation is considered to be related to the Cananéia Formation which has been described in São Paulo State and is probably 'Last' Interglacial in age (Suguio and Petri, 1973; Petri and Suguio, 1973).

The present barrier is believed to have formed at about 7150 BP, at the same time as the first barrier at Lagoa do Padre. However, unlike the barriers at Lagoa do Padre and Lagoa de Guaratiba, this barrier was not subsequently breached. The final transgressive overlap at this site is similar in age to the final transgressive overlap at Lagoa do Padre: 2460 ± 55 BP compared with 2590 ± 65 BP.

In Figure 4.24d, peaks of *Fragilaria* Lyn. frequently occur during times when tidal inlets are believed to have been present and troughs when they are absent. If the periods when inlets prevail are taken to be indicative of

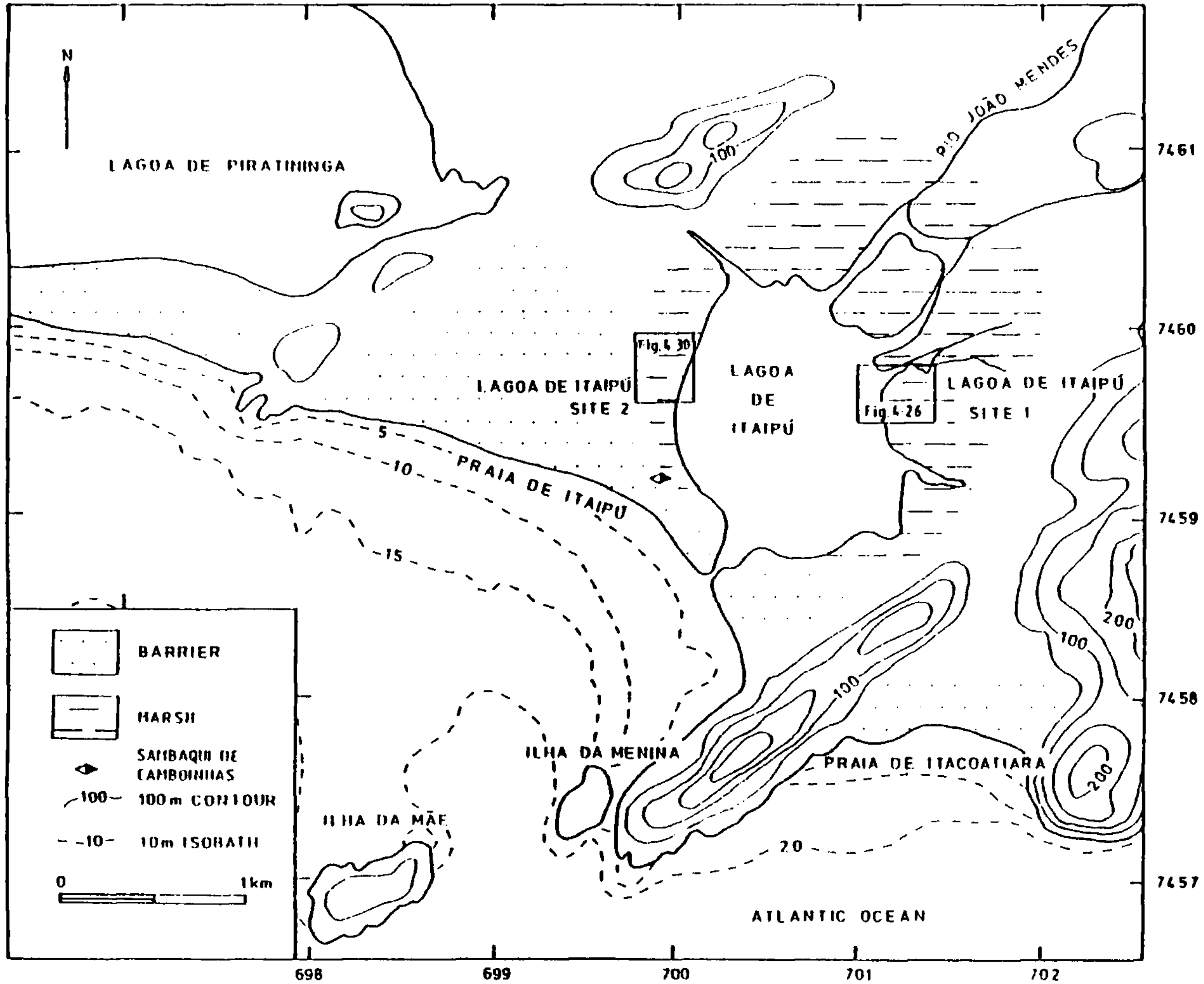


Figure 4.25 A map of Lagoa de Itaipú showing the location of sampling sites and the Sambaqui de Camboinhas

transgressive tendencies this is the reverse of what is expected, as the *Fragilaria* Lyn. peaks are supposedly indicative of regressive tendencies. It results from the fact that the *Fragilaria* Lyn. species present are fresh-brackish and so are most common during the more saline phases at this site.

4.6 Lagoa de Itaipú

Lagoa de Itaipú (Figure 4.25) is a small lagoon covering approximately 1.5 km^2, around which lies approximately 2 km^2 of marsh. This is mostly located to the northeast of the lagoon, from where five streams enter. The largest of these is the Rio João Mendes which drains most of the adjoining flat valley. The lagoon lies between the steeply rising crystalline ranges of the Serra Malheiro, in the west and the Serra da Tiririca in the east. It is (Muehe, 1982) protected from the ocean by a single, merged barrier. In the west there is a considerable expanse of sand, extending inland approximately 1.3 km from the beach, while in the east the barrier is only about 150 m across.

Offshore the situation is somewhat different from that at Maricá or Itaipu-Açu. The continental shelf slopes more gently and protection is provided by three islands - Ilha do Pai, Ilha da Mãe and Ilha da Menina - and the headland of the Morro das Andorinhas. Consequently the coastal waters are generally calmer than along the more exposed coast, immediately to the east.

4.6.1 Presentation of results for Lagoa de Itaipú Site 1

Lagoa de Itaipú Site 1 is situated on the eastern margin of the lagoon on relatively flat marshland, which is in the process of being developed for housing.

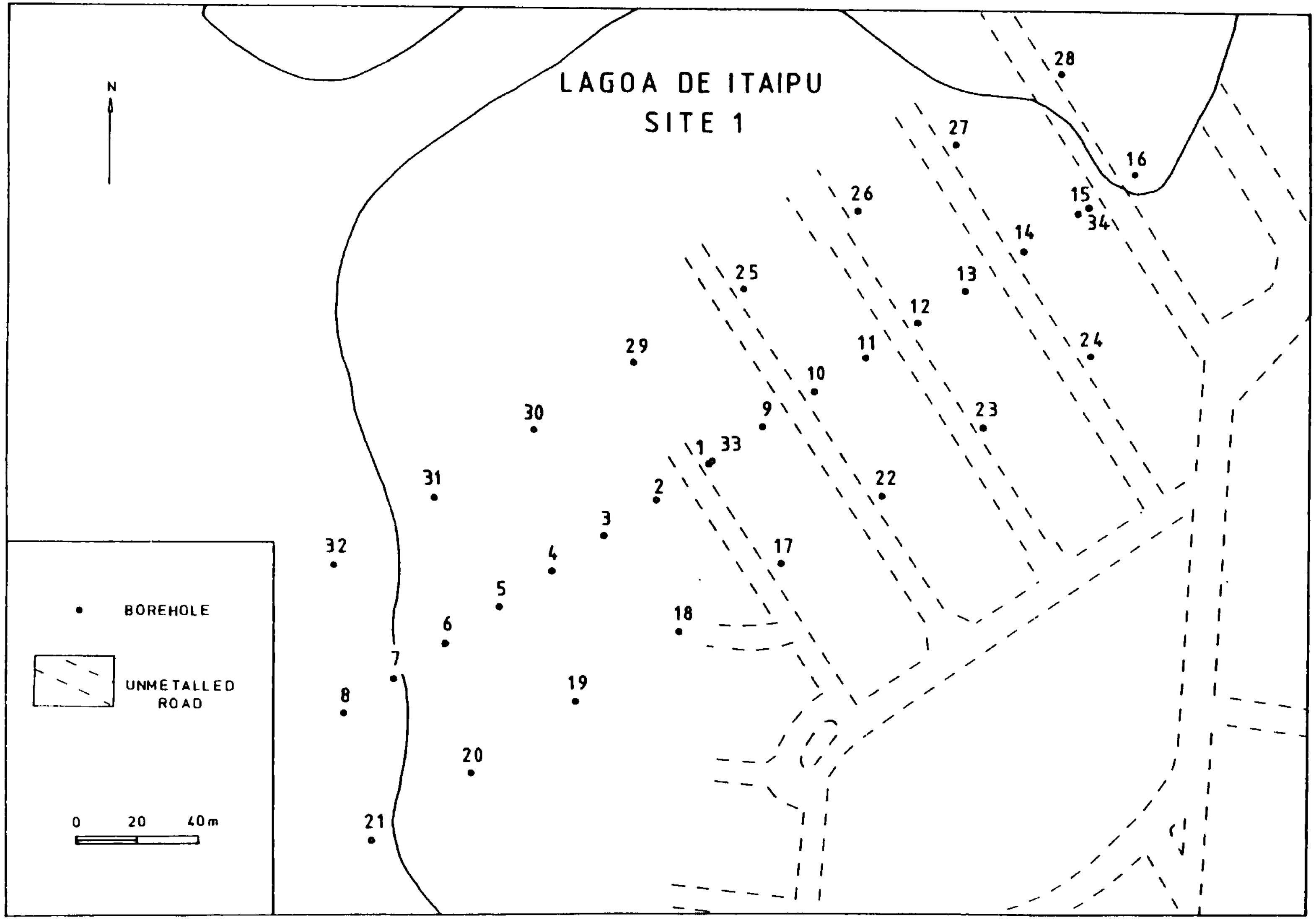


Figure 4.26 A map of Lagoa de Itaipú Site 1 showing the location of boreholes

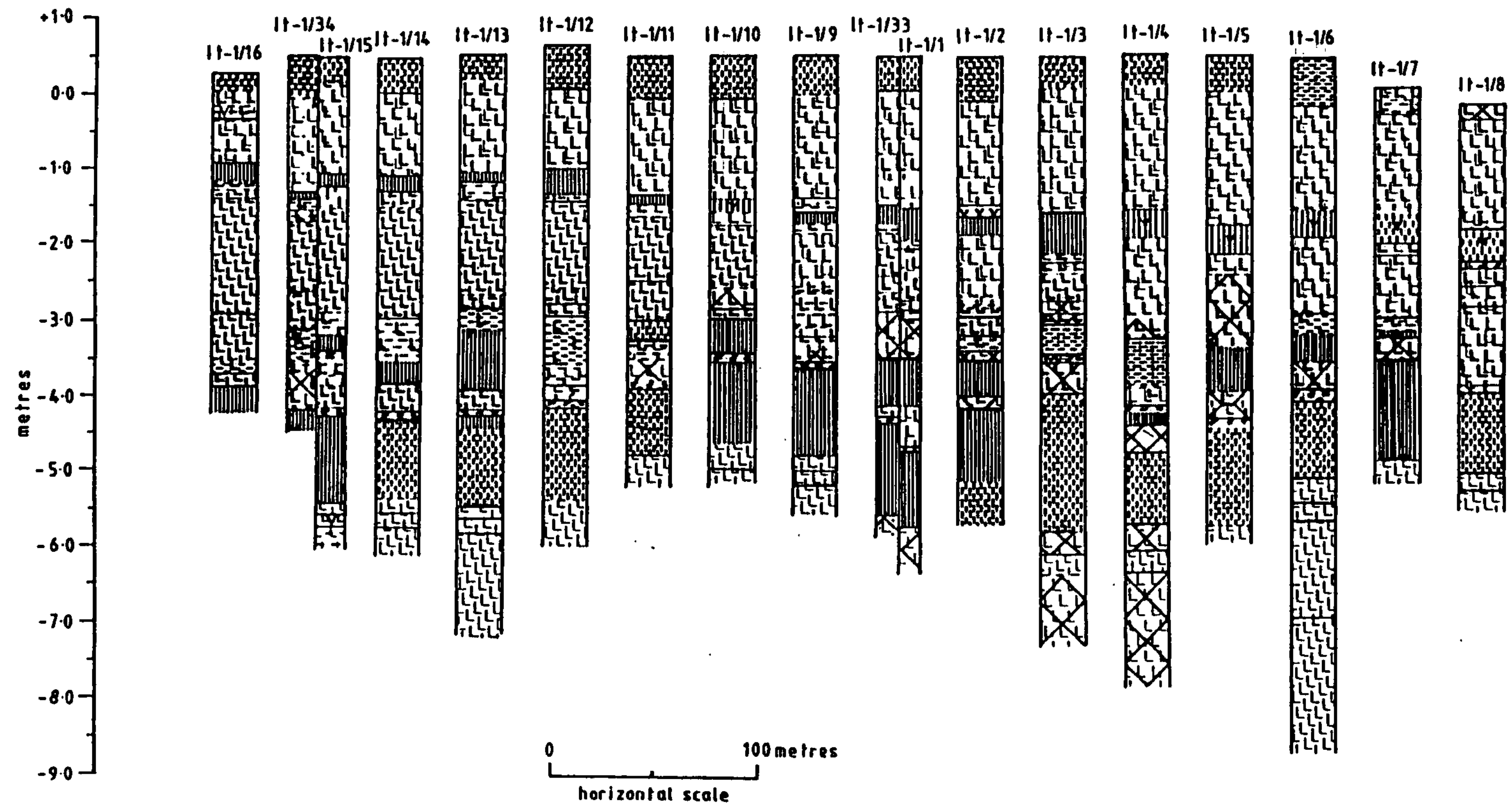


Figure 4.27 A diagram showing the stratigraphy along the main northeast-southwest transect at Lagoa de Itaipú Site 1

4.6.1.1 Stratigraphic analysis

At this site (Figure 4.26) there are three transects 80 m apart, running from northeast to southwest. Along the central transect the sampling interval is 40 m and along the outer transects it is 80 m. There are 34 boreholes.

Clay and silt with varying proportions of organic matter intercalate four peat strata (Figure 4.27). Beneath the basal peat is a muddy silt with clay and sand, the proportion of the latter decreasing with depth. At It-1/6 this extends to an altitude of at least -8.74 m. The possible surface configuration of the muddy silt is shown in Figure 4.28a, which suggests that a curving, linear depression ran from northeast to southwest, gradually increasing in depth.

The surface of the basal peat (Figure 4.28b) comprises a series of hollows separated by ridges which mask the underlying depression. The thickest peat accumulation occurs in the depression and the thinnest on the higher ground. It is a dark reddish brown to very dark brown, well humified, woody, herbaceous peat, ranging in thickness from 0.39 to 1.83 m. At It-1/4 it is interesting to note that the 1.52 m thickness of peat envelops a 0.35 m stratum of brown, fine detrital mud. Over most of the site the surface of the peat is marked by a thin layer of charcoal. Investigation under magnification indicates that this was not completely charred.

The deposit which separates the basal from the overlying peat is variable from borehole to borehole. Generally immediately over the charcoal is a rather distinctive, pale-coloured stratum, ranging from light yellowish brown to pale brown, which has been described as a silty, muddy clay with a possible siliceous mud fraction. At It-1/5 a thin (7 cm thick) white stratum appears between the clay and charcoal which is believed to be a clayey, siliceous *limus*. It became extremely light in weight when dry, which

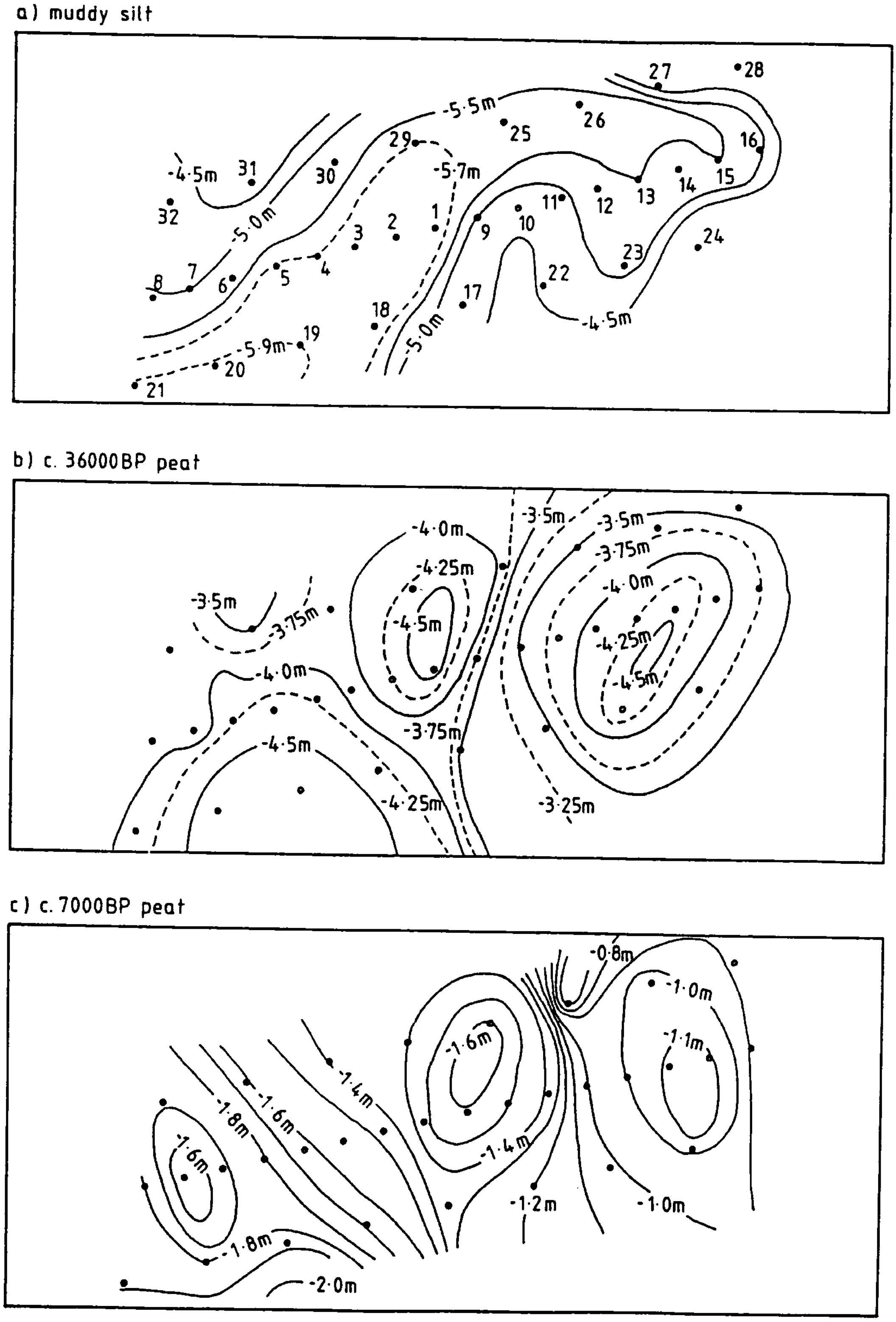


Figure 4.28 Maps showing the possible surface configuration of selected sedimentary strata at Lagoa de Itaipú Site 1

supports this assertion and the possibility that siliceous mud is present within the pale brown stratum. This is overlaid by a dark brown to very dark greyish brown, organic, silty clay. Charcoal fragments are found at various levels.

The peat which covers this deposit, which is also of variable thickness (0.10-0.75 m) is intermittent and shows no clear altitudinal or spatial pattern. It is very dark brown in colour and ranges from a well humified, woody, herbaceous peat to clayey, organic matter.

This is overlaid by an organic clay, which includes pale strata thought to contain a possible siliceous mud fraction. At the top of this clay, just below the third peat stratum, a charcoal layer is recorded at It-1/8 and It-1/23. At numerous boreholes the clay immediately below the peat is black in colour and at It-1/21 contains charcoal fragments. At others (It-1/14, /15, /22 and /27) the clay is in hard granules.

The third peat stratum, a very dark brown, well humified, woody, herbaceous peat, shows a clear altitudinal and spatial pattern illustrated in Figure 4.28c while the surface undulates gently, it slopes to the southwest at an angle of 0.18°. The recorded thickness ranges from 0.12 m to 0.57 m, increasing towards the ocean.

There is an intermittent covering of sand over the peat, particularly evident along the most southerly transect. 0.07 and 0.08 m of pure sand have been deposited over the peat at It-1/18 and /19 respectively, and 0.02 to 0.16 m of predominantly sandy sediment has been laid down at seven other boreholes (one in the central transect and three in each of the adjacent transects).

The sand or peat is overlaid by a muddy, silty clay, which, though variable, is relatively consistent from borehole to borehole. Where there is variation, it is generally siltier towards its base. At It-1/30 and /31, however, a 3 cm thick stratum of silty sand intercalates the silty clay sloping at an angle of 0.4° from -0.71 m at It-1/30 to -0.96 m altitude at It-1/31. The silty clay is covered by the surface stratum, which is a very dark brown, humified, herbaceous peat. A complete absence of ligneous roots distinguishes this from earlier peats. Its surface is essentially flat.

4.6.1.2 Particle size analysis

Particle size analysis was carried out on core It-1/33. A tabular presentation of the results is in Appendix III, together with a detailed stratigraphic description of the borehole. Comparison shows that there is generally very good agreement, although there are three strata where the field descriptions are at variance with the laboratory analyses. In stratum 1 (Ag2, Ga1, Ld^{3}1) there are approximately equal parts of silt and sand, while in strata 12 and 18 (As3, Ag1) the clay content is approximately double that of silt. Such ratios cannot be adequately expressed using the Troels-Smith (1955) scheme.

4.6.1.3 Diatom analysis

Diatom analysis was carried out on It-1/33 (Figure 4.29). Below 3 m depth the sediment is very diatom poor; taking samples at 10 cm intervals, only six levels contained countable concentrations of diatoms to a depth of 6.36 m.

Salinity phase It-1/33a, which extends from the upper muddy, sandy silt into the first few centimetres of the basal peat, is fresh-brackish in character. The phase is clearly dominated by fresh-brackish taxa though there are taxa ranging from fresh to brackish. The dominant species change through the phase. At the base of the phases benthic *Fragilaria brevistrata* Grun. is most common, but is succeeded by planktonic *Melosira ambigua* (Grun.) O.Müll. with benthic *Cymbella ventricosa* Kütz.. Within the basal peat *C. ventricosa*

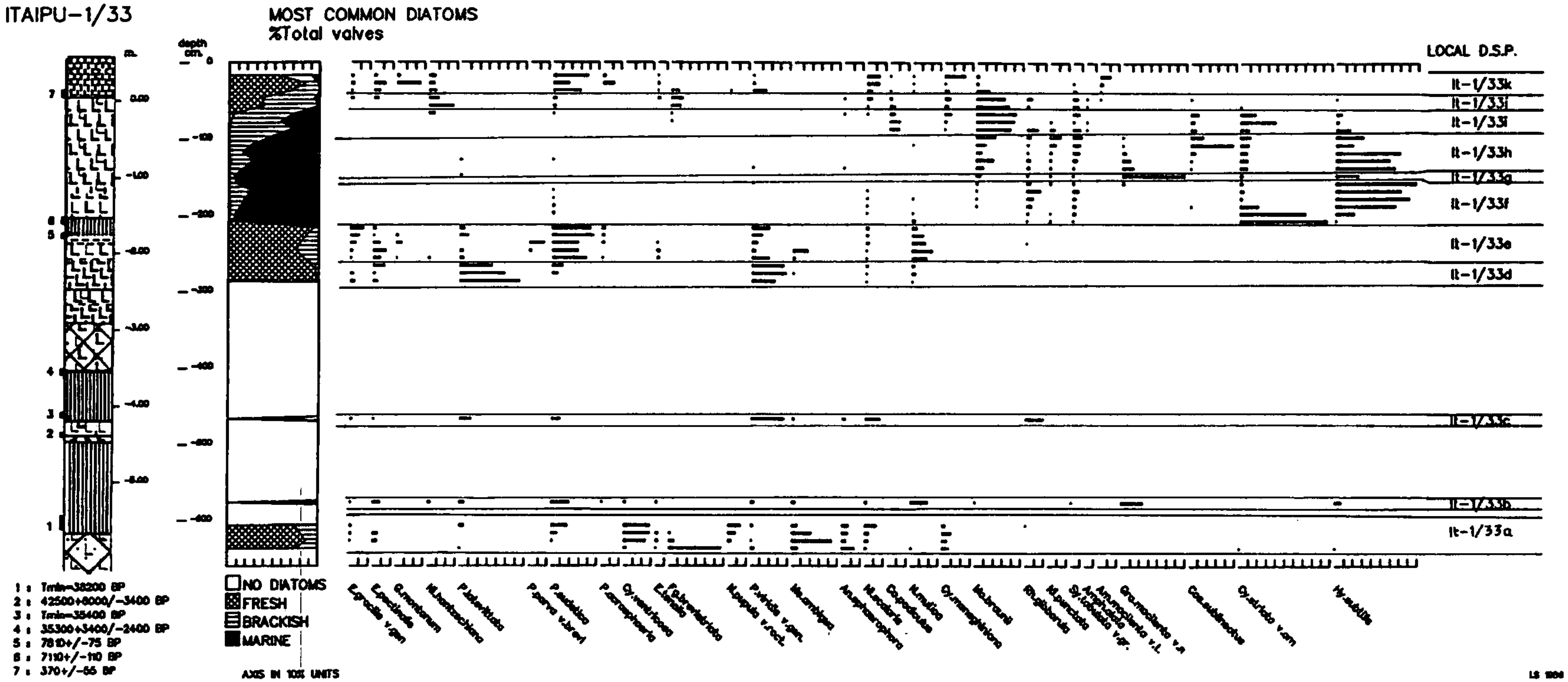


Figure 4.29 A diatom diagram showing the most common diatoms enumerated in core It-1/33 (see Appendix IV for the the rare diatoms)

Kütz. dominates, with fresh *Pinnularia sudetica* Hils. responsible for an increased fresh presence.

Above this the basal peat is then very diatom poor, with the exception of a level at -5.27 m (It-1/33b) which is characterized by an unusual distribution of salinity groups. Benthic fresh diatoms are dominant, but there are also significant percentages of brackish-fresh and marine-brackish, benthic diatoms. The most common diatom is the marine-brackish *Grammatophora macilenta* var. *nodulosa* Grun., while *P. sudetica* Hils. is the most common fresh and *Navicula mutica* Kütz. the dominant brackish-fresh species.

There is only one level, within the clayey silt which separates the basal from the overlying peat, that contains countable concentrations of diatoms. This is just below the overlying peat at -4.17 m altitude and, in terms of salinity characteristics, is similar to It-1/33a. It-1/33c is, however, dominated by *Pinnularia viridis* var. *genuina* A.Cl. and there is a greater brackish presence, notably of *Rhopalodia gibberula* (Ehr.) O. Müll.. Above this phase is another impoverished zone.

Countable concentrations are found between -2.37 m altitude and the surface. Phase It-1/33d, in the clay of stratum 13, is characterized by fresh and fresh-brackish taxa and is heavily dominated by *Pinnularia viridis* var. *genuina* A.Cl. and *P. latevittata* Cl.. This phase is succeeded by It-1/33e which is essentially fresh, dominated by *P. sudetica* Hils., but displays a marked increase in brackish taxa, especially *Navicula mutica* Kütz.. This extends from stratum 13 into the peat of stratum 16.

A very abrupt change occurs towards the top of the peat stratum between It-1/33e and It-1/33f. The latter is a marine phase dominated in turn by *Cyclotella striata* var. *americana* A.Cl. and *Hyalodiscus subtilis* Bail.. It-1/33h is also marine in character, dominated by *H. subtilis* Bail. at all but one level (-0.57 m altitude) where *Coscinodiscus sublineatus* Grun. is prevalent. These are separated by the marine-brackish phase It-1/33g, at -0.97 m altitude, which is dominated by benthic *Grammatophora macilenta* var. *nodulosa* Grun..

It-1/33i is a brackish and marine phase, dominated by *Mastogloia braunii* Grun. and *Cyclotella striata* var. *americana* A.Cl.. *M. braunii* Grun. is also prevalent in the brackish and fresh phase of It-1/33j where *Nitzschia hantzschiana* Rabh. and *Fragilaria brevistriata* Grun. are over the most numerous fresh and fresh-brackish taxa. Finally It-1/33k is a fresh phase dominated by *Pinnularia sudetica* Hils..

The marine influenced salinity phases extend from the peat through the silty clay of stratum 17 and into that of stratum 18. It-1/33j extends from stratum 18 into stratum 19, the surface peat, where it is succeeded by It-1/33k.

4.6.2 Presentation of results for Lagoa de Itaipú Site 2

Lagoa de Itaipú Site 2 is found on the western margin of the lagoon on marshland adjacent to the barrier sand (Figure 4.25).

4.6.2.1 Stratigraphic analysis

At this site there are two transects from northwest to southeast, joined by three, 160 m long, northeast to southwest transects. Boreholes are placed at 40 m intervals along the transects (Figure 4.30).

The stratigraphic sequence is dominated by fine clastic sediment with two peat strata (Figure 4.31). The basal peat has accumulated over a dark greyish brown, sandy, muddy, clayey silt, which (at It-2/2 and 2/3) lies over an olive grey, clayey silt. The possible surface configuration of the dark greyish brown, clayey silt is shown in Figure 4.32a, which suggests a gently

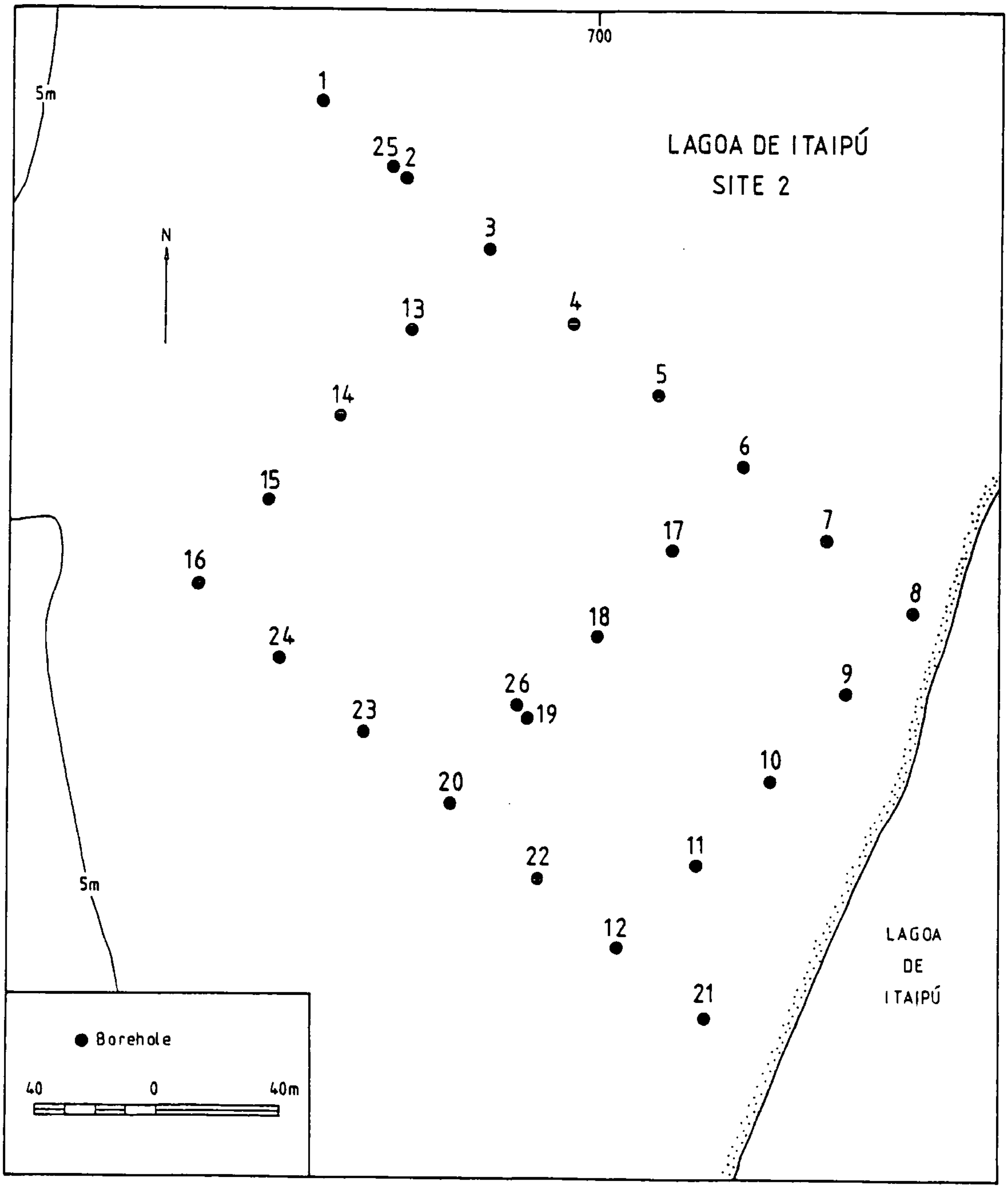


Figure 4.30 A map of Lagoa de Itaipú Site 2 showing the location of boreholes

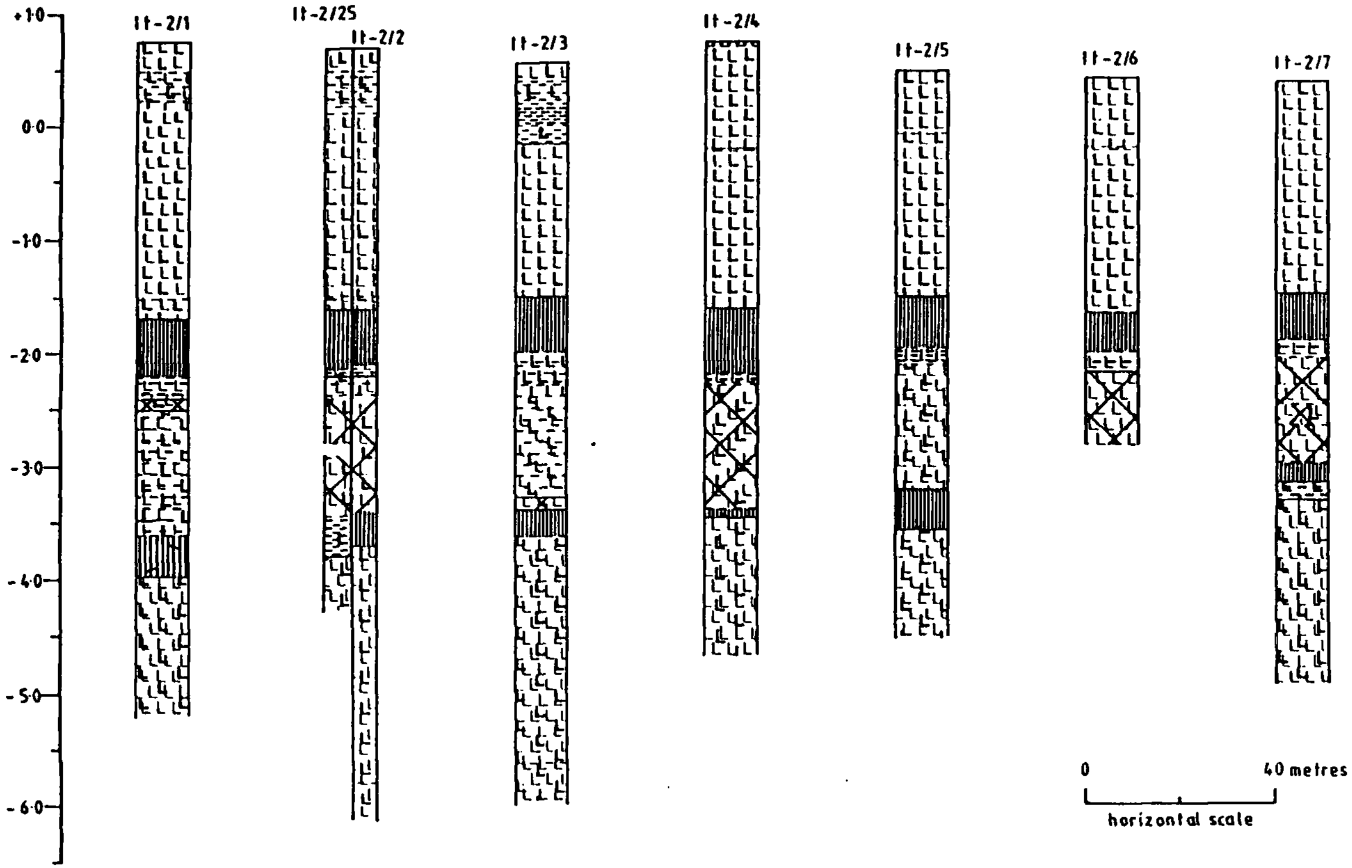


Figure 4.31 A diagram showing the stratigraphy along the main northwest-southeast transect at Lagoa de Itaipú Site 2

undulating surface sloping towards the southwest at an angle of approximately 0.06°. The recorded altitudinal range of the surface is 2.1 m, which is identical to the range recorded at Lagoa de Itaipú Site 1 (Figure 4.28a). At this site, however, the slope falls from a point 0.75 m higher than the highest recorded point at Site 1.

The basal peat is variable in composition. Over most of the site it is a very dark brown, herbaceous peat with woody detritus, but at It-2/8, /14, /15 and /25 it is a very dark brown, silty, clayey peat (with approximately 50% organic matter). Interestingly the latter is also found below the peat at It-2/7, but above the peat at It-2/10. The thickness of the basal peat stratum ranges from 0.04 to 1.26 m, with a mean recorded thickness of 0.52 m. The greatest accumulations have developed at the lower altitudes. Its possible surface configuration is shown in Figure 4.32b. The peat is overlaid by an intermittent stratum of charcoal which is encountered in 25% of the boreholes. It has a recorded thickness of between 1 and 4 cm.

The peat or charcoal is covered by a clayey, muddy silt of varying composition, but with at least 50% silt and, with one exception, not less than 25% fine detrital mud. Between this and the second peat stratum is a black, clayey, muddy silt which occasionally contains woody or herbaceous detritus. No charcoal was observed.

The second peat is composed of very dark brown, well humified, herbaceous material and is less variable than the basal peat in respect of both composition and thickness. Woody fragments are found towards the top of the stratum at more than 50% of the boreholes, while ligneous roots are found at three of them. At It-2/14 there is a 0.17 m thick, silty, sand stratum within the peat. It seems likely that the surface slopes into a linear

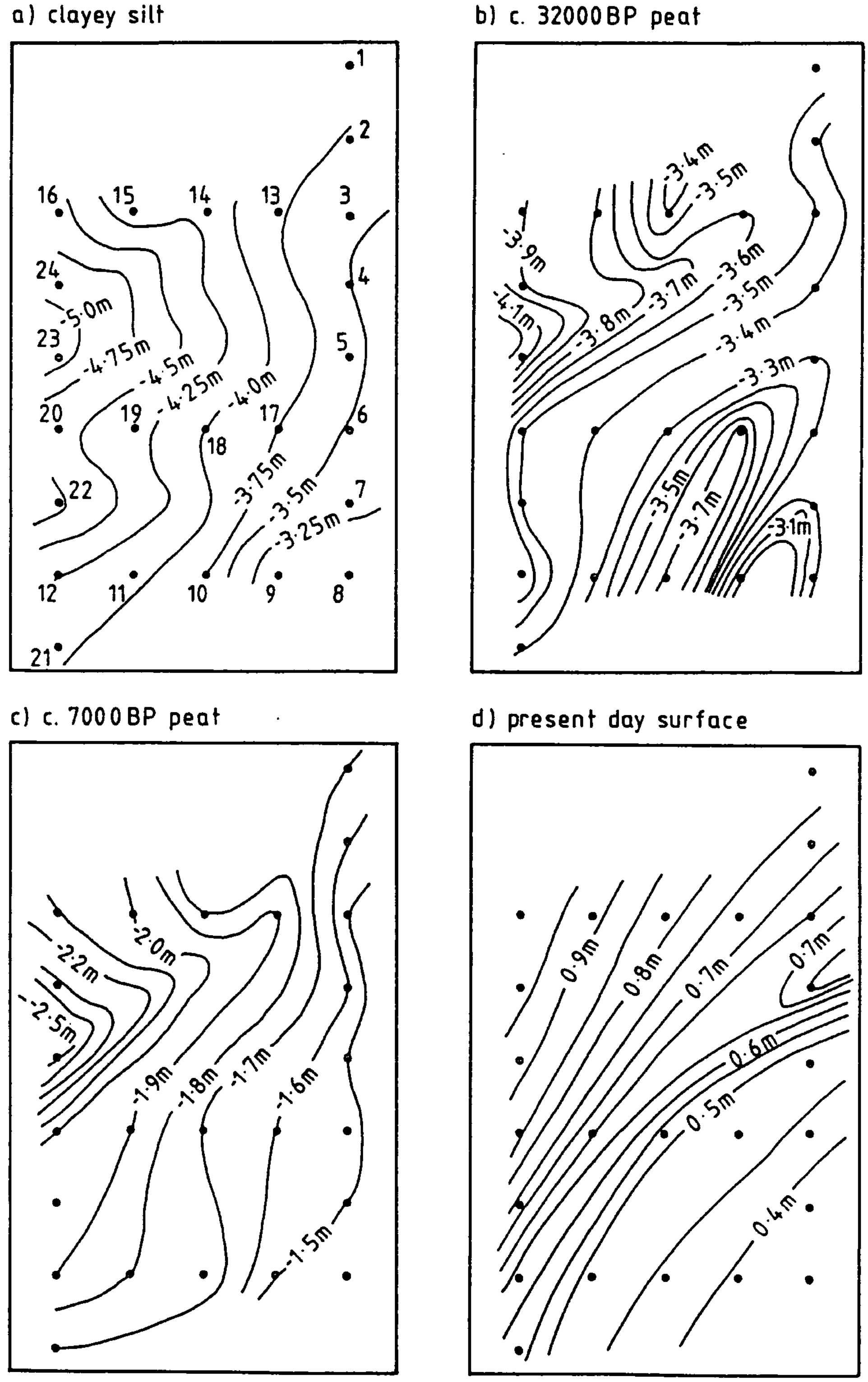


Figure 4.32 Maps showing the possible surface configuration of selected sedimentary strata at Lagoa de Itaipú Site 2

depression running from It-2/13 to /24 (Figure 4.32c). The recorded thickness ranges from 0.29 to 0.67 m, with a mean recorded thickness of 0.43 m.

1 to 4 cm of pure sand lie over the peat at It-2/1, /4 and /19, while 3 cm of clayey, silty sand are found at It-1/26. Elsewhere a trace of sand is recorded in the lower levels of the silty clay, which over much of the site extends to the surface. At It-2/12 an *Anomalocardia brasiliana* (Gmelin) fragment was found in the stratum extending from -1.7 to -0.3 m altitude.

In the northwest of the site (It-2/1 to /3 and It-2/13 to /15) the silty clay deposition was interrupted by the accumulation of relatively organic rich sediment with between 25% and 100% organic matter, the remainder being silty clay. From its thickest (0.65 m) at 0.45 m altitude it rises and thins to the north (0.35 m thick at 0.52 m altitude) This stratum is overlaid by silty clay.

In the southwest of the site the silty clay is overlaid by sand which thickens to the northwest, where it dips and is, in turn, covered by silty clay. Generally, however, the sand is exposed at the surface. It ranges in thickness from 0.02 to 1.08 m. There is also a thin sand covering at It-2/8, close to the present lagoonal margin.

The present-day surface slopes at an angle of 0.15° from west to east (Figure 4.32d).

4.6.2.2 Particle size analysis

Particle size analysis was carried out on core It-2/26. A detailed stratigraphic description of this core, together with a tabular presentation of the particle size analysis results is in Appendix III. There is good agreement for all but three strata. In stratum 1 (Ag3, As1), the dark greyish brown, clayey silt which lies below the basal peat, the sand content was underestimated and code Ag2, As1, Ga1 is preferred. In stratum 7 (Ga2, As1, Ag1), the sandy stratum covering the second peat at this borehole, the silt component should be replaced by sand making it Ga3, As1. The stratum 12 description cannot be improved, but is inadequate because there are approximately equal proportions of clay, silt and sand. The inaccuracy in stratum 1 may affect the whole site.

4.6.2.3 Diatom analysis

Diatom analysis on core It-2/26 reveals a broadly similar sequence of salinity phases to that recorded at It-1/33. Diatom poor phases are restricted to the organic strata.

Biostratigraphic salinity phase It-2/26a, (Figure 4.33) which is brackish and fresh-brackish in character is equivalent to lithostratigraphic stratum 1. It is dominated by brackish diatoms, notably *Campylodiscus clypeus* Ehr., although the percentage of *Melosira ambigua* (Grun.) O.Müll. is increasing. Above this, at the bottom of the basal peat, phase It-2/26b is essentially fresh-brackish and dominated by *M. ambigua* (Grun.) O. Müll.. This is succeeded by an impoverished zone which extends to within a few centimetres of the top of the peat.

It-2/26c, which marks the top of the peat and the base of stratum 3, the dark greyish brown, clayey, muddy silt, is fresh and fresh-brackish (approximately 50:50). *M. granulata* var. *typica* A.Cl. and var. *angustissima* O. Müll. dominate the fresh-brackish assemblage, while *Pinnularia latevittala* Cl. is the most common fresh diatom. This is succeeded by a fresh phase, It-2/26d, which extends to the top of stratum 3. It is dominated by *Pinnularia* Ehr. species and *Eunotia* Ehr. species which make up between 88

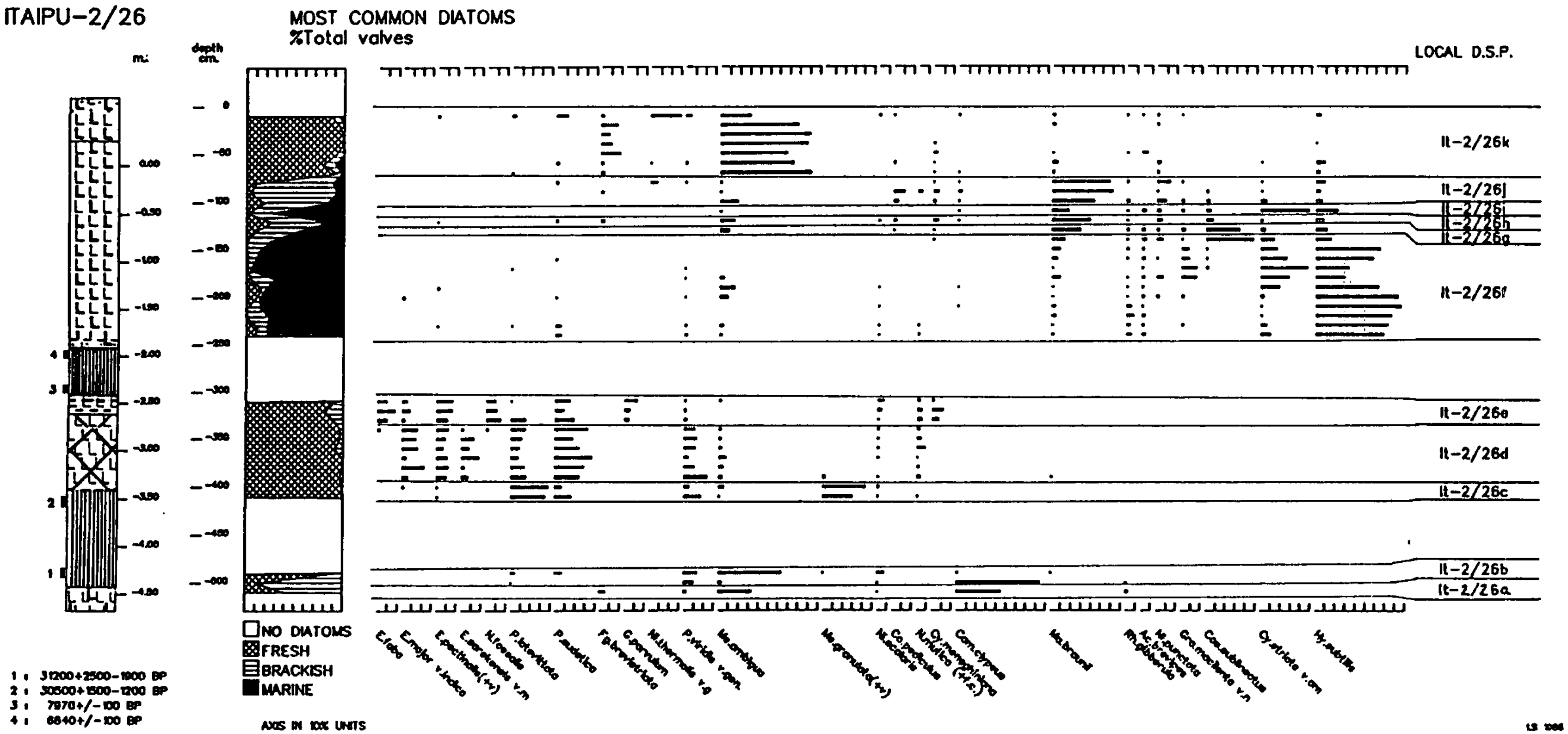


Figure 4.33 A diatom diagram showing the most common diatoms enumerated in core It-2/26 (see Appendix IV for the rare diatoms)

and 97% of each assemblage. *P. sudetica* Hils. is the most common species throughout.

It-2/26e covers stratum 4, the very pale brown, clayey, muddy silt, and stratum 5, the black, clayey, organic silt which lies immediately below the second peat stratum. It is predominantly fresh (70-80%) but there is a presence of brackish-fresh diatoms (9-19%). *Pinnularia* Ehr. species and *Eunotia* Ehr. species are common but only make up between 55 and 62% of each assemblage.

An impoverished zone extends through the peat of stratum 6, the clayey sand of stratum 7 and into the overlying silty clay of stratum 8. However, small numbers of marine *Hyalodiscus subtilis* Bail. valves were observed from just below the top of the peat. It-2/26f is a marine phase which extends through stratum 8 and into stratum 9; also a silty clay. Although the consistently high marine presence makes this a single salinity phase there is a marked succession at the species level. From the base to -1.28 m altitude *H. subtilis* Bail. is clearly dominant, then between -1.28 and -1.08 m altitude *Cyclotella striata* var. *americana* A. Cl. and *H. subtilis* Bail. are most common and there is a marked rise in *Grammatophora macilenta* var. *nodulosa* Grun.. Between -1.08 and -0.88 m altitude *H. subtilis* Bail. dominates, while at -0.78 m *Coscinodiscus sublineatus* Grun. is most common.

Following this phase, there are a series of relatively rapid transitions from phase to phase. It-2/26g is marine and brackish, with *C. sublineatus* Grun. the prevalent marine diatom and *Mastogloia braunii* Grun. the most notable brackish species. It-2/26h is characterized by fresh, brackish and marine diatoms but the brackish, particularly *M. braunii* Grun., are dominant. The next phase, It-2/26i, is marine in character and dominated by *Cyclotella striata* var. *americana* A.Cl. with *Hyalodiscus subtilis* Bail.. It-2/26j, the upper limit of which marks the top of stratum 9 is brackish, with *M. braunii* Grun. clearly dominant.

It-2/26k is a fresh-brackish phase. Throughout stratum 10, another silty clay, planktonic *Melosira ambigua* (Grun.) O. Müll. is prevalent. No count was made in stratum 11, the clayey sand, but the surface of stratum 12, a sandy, silty clay is dominated by *M. ambigua* (Grun.) O. Müll. and benthic *Nitzschia thermalis* var. *genuina* May..

4.6.3 The sedimentary history of Lagoa de Itaipú

The radiocarbon dates (Table 4.1) from the lower peat beds at site 1 and the basal peat at site 2 indicate that the lower sequence is likely to have formed during a period of time equivalent to interstadial conditions during the last full glacial age in northwest Europe and North America.

The basal peat at Site 1 is the oldest recorded peat around Lagoa de Itaipú. It formed over a muddy, sandy silt which was deposited in a moderate energy environment in oligohaline water. The linear depression illustrated in Figure 4.28a suggests that a stream may have flowed through the site prior to peat accumulation. This is supported by the presence of relatively high counts of *Cymbella ventricosa* Kütz. in borehole It-1/33, which appears to have sampled the mid-channel sediment. *C. ventricosa* Kütz. is stipitate (with mucilaginous stalk), adapted to life in flowing water.

The accumulation of peat is presumed to reflect a transition from an aquatic to a semi-terrestrial environment, the presence of ligneous roots suggesting that the site was dry for at least part of the year. The base of the peat has been dated to T min = 38200 BP and its surface to T min = 36000 BP and 42500 + 6000, -3400 BP (see 4.2). The dominance of *C. ventricosa* Kütz. at the base of the peat suggests that water was still flowing through the

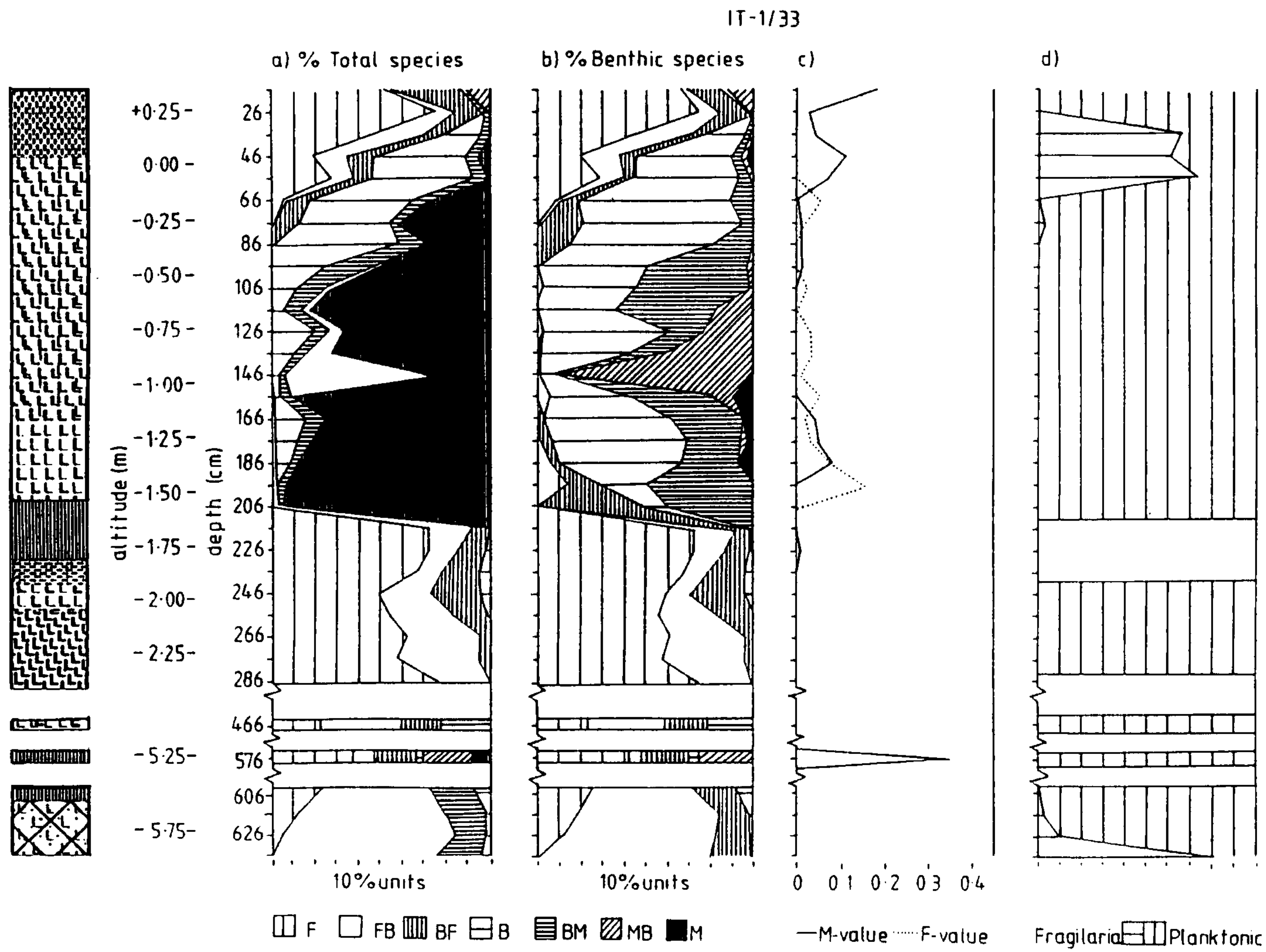


Figure 4.34 A diagram showing (a) the % total diatom species present, (b) the % benthic diatom species present, (c) fresh and marine allochthonous diatom groups expressed as ratios of the autochthonous group and (d) the *Fragilaria* - Planktonic representation in core It-1/33

channel as peat began to accumulate. The remaining peat is diatom poor with the exception of a level at -5.27 m altitude (It-1/33b) which, as noted in 4.6.1.3, has a rather unusual diatom distribution. The benthic population, as shown in Figure 4.34b, comprises three main diatom salinity classes - namely fresh, brackish-fresh and marine-brackish. Figure 4.34c indicates that the marine-brackish valves are likely to be allochthonous. They could, however, relate to a contemporaneous marine advance, or have been eroded from marine sediment that had been deposited up-valley during an earlier interglacial.

The thin layer of charcoal which covers most of the peat may have been transported from up-valley and deposited at the site, or been *in situ*. Irrespective of where the fire occurred it was probably a light burn, as the charcoal is not completely charred. Until recently, the age of the underlying peat (>36000 BP) seemed to indicate that this was a natural burn, possibly resulting from a lightning strike, as man was believed not to have arrived in South America before 20000 BP (Meggers, 1981). However, radiocarbon dates, from the large painted rockshelter of Boqueirão do Sitio da Padre Furada, Piaui in northern Brazil, establish that early man was probably living in South America at least 32000 years ago. Guidon and Delibrias (1986) dated the periodic occupation of the site from 32160 ± 1000 BP to 6160 ± 130 BP, the oldest dates coming from charcoal taken from the lowest hearth found at the site, at a level where many lithic artefacts were recovered. This shows clearly that early Brazilian man was manipulating fire. In the light of this evidence, the possibility of human interference at Itaipú around this time and later, as indicated by other charcoal deposits around the lagoon, must now be considered, although no corroborative archaeological evidence has been found for such an early occupation (the earliest recorded occupation is on the barrier and is dated at 7958 BP, Kneip *et al.* (1980, 1981)). Nevertheless, if fire had destroyed the vegetation up-valley, either naturally or through the influence of man, it may explain the influx of largely diatom poor, clayey silt over the charcoal.

The second peat at Site 1 and the lower peat at Site 2 are similar in character, are at a similar altitude and probably formed at the same time. The range of dates (Table 4.1) probably reflects errors in the ^{14}C method, rather than age differences of 3000 years over relatively short distances. The diatom salinity phases immediately below the Site 1 peat and at the base of the Site 2 peat add support to the hypothesis that they are contemporaneous. Both are dominated by fresh-brackish diatoms - notably *Pinnularia viridis* var. *genuina* A.Cl. in the benthic population - and are indicative of oligohaline water salinity.

The sediment below the Site 2 peat is a sandy, clayey silt, similar in character to that below the basal peat at Site 1 and unlike the clayey silt which covers it, which suggests that it predates peat growth at Site 1. This is supported by a very sharp change in the diatom successions between the base of the peat and the underlying clastic deposit. The latter, in which the fresh-brackish valves are probably allochthonous (Figure 4.35c), is dominated by brackish diatoms and represents α mesohaline water conditions. As the sandy clayey silt is at a higher altitude at this site than at Site 1, it seems probable that it would have been dry during the period of peat growth at Site 1. The transition is interpreted as a bio- and lithostratigraphic hiatus which makes it difficult to date the clastic deposit.

It seems likely that peat growth came to an end at both sites in *c.* 32500 BP, when the site was inundated with water and predominantly fine grained clastic sedimentation resumed. At Site 2 (Figure 4.35b) this contains mostly fresh and fresh-brackish diatoms which represent fresh to oligohaline water.

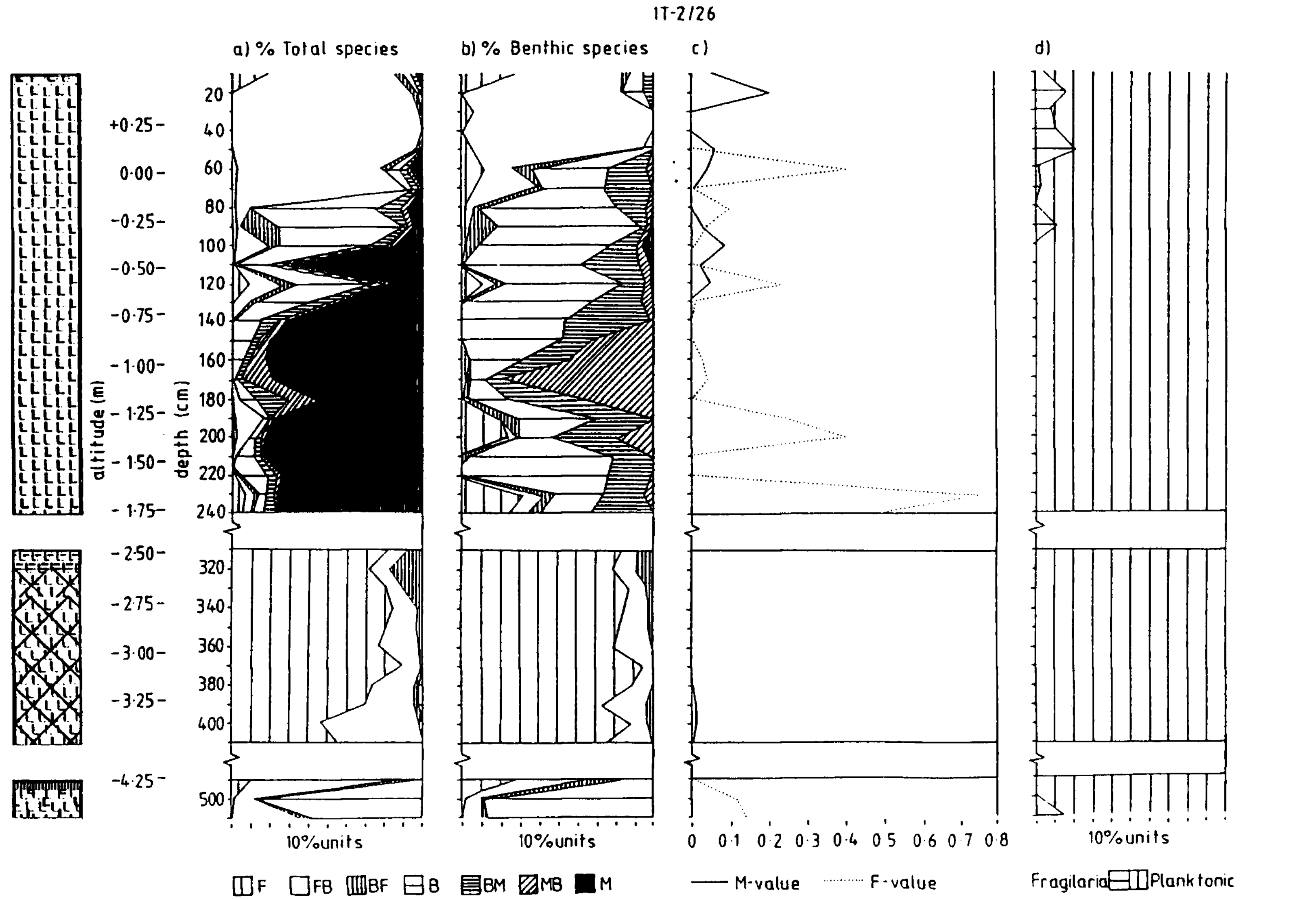


Figure 4 .35 A diagram showing (a) the % total diatom species present, (b) the % benthic diatom species present, (c) fresh and marine allochthonous diatom groups expressed as ratios of the autochthonous group and (d) the *Fragilaria* - Planktonic representation in core It-2/26

Following an impoverished zone, a similar picture is found at Site 1 (Figure 4.34b).

At both sites, just below the overlying peat, the water is clearly more saline, possibly approaching α mesohaline. This marks the only change in the continuous diatom succession at site 2 which could be considered to represent a biostratigraphic hiatus of the magnitude expected between an interstadial and the following interglacial. It occurs approximately 30 cm below the base of the Holocene peat and is accompanied by a lithostratigraphic change which is believed to mark the onset of Holocene sedimentation at Lagoa de Itaipú.

Before Holocene sedimentation is described and discussed in detail, it is appropriate to consider the pre-Holocene sedimentary history of the site. The lower peats intercalating clastic sediment may indicate either water-level fluctuation in lagoons consequent upon changes in a high interstadial sea level, or water-level fluctuations resulting from climatic oscillations.

The presence, in a single layer within the basal peat of allochthonous marine diatoms, notably *Grammataphora macilenta* var. *nodulosa* Grun. and *Hyalodiscus subtilis* Bail., provides evidence for a high interstadial sea level. Thom (1973) marshalled evidence from around the world that pointed to a climatic amelioration around 35000 ± 10000 BP and sea levels attaining altitudes of 30 m below present-day sea level and perhaps higher locally. For the Brazilian continental shelf Kowsmann *et al.* (1977) and Kowsmann and Costa (1979) presented evidence for a rapid fall of sea level between 23050 ± 550 and 19910 ± 330 BP from 28 m to 115 m below present MSL. The diatom assemblage from Lagoa de Itaipú may indicate a maximum high interstadial sea level at present-day altitudes of -4 to -6 m between 30500 + 1500, - 1200 BP and 42500 + 6000, -3400 BP; the period identified by

Heusser *et al.* (1981) as a relatively warm, wet interstadial in southern Chile. There is, however, no stratigraphic evidence to indicate that the site was subject to inundation during this period and the litho- and biostratigraphic evidence from around the base of the peat suggests that the silt/peat transitions; if related to sea-level movement, would be a regressive overlap.

An alternative explanation is that the sequence resulted from fluctuations between relatively wet and relatively dry periods during a humid climatic phase. Brackish diatoms would be favoured by an increase in salinity resulting from evaporation. Prance (1978) summarized the evidence for climatic oscillations after 36000 BP in Amazonia that comprise a succession of wet-cold, dry-hot and dry-cold conditions.

Holocene sedimentation appears to have begun in oligohaline to α mesohaline water in a very low energy environment. This phase came to an end as peat began to accumulate at both sites at *c.* 7890 BP, or earlier, marking a regressive overlap. Three samples have been dated from the base of the peat; one from Site 1 (7810 ± 75 BP) and two from Site 2 (7970 ± 100 BP and 8850 ± 110 BP). Because two samples have yielded a similar age it is possible that the 8850 BP date is in error, contaminated by older carbon. As humic acid was not removed by pretreatment at Kiel it is also possible that the younger samples were contaminated by dissolved humus percolating down from higher levels, but as a regressive overlap is also indicated at Lagoa do Padre at *c.* 7200 BP the older date is rejected.

Peat growth continued until *c.* 6988 BP when clastic sediment was deposited in polyhaline water, marking a very clear transgressive overlap. Four samples were dated from the top of the peat and yielded similar ages at both sites (7110 ± 110, 6860 ± 110, 7140 ± 110 and 6840 ± 100). A thin, intermittent, layer of sand was recorded over the peat at both sites, but the silty clay which predominates is indicative of low energy deposition. This suggests the presence of a barrier with a tidal inlet, protecting the site from the higher energy regime of the Atlantic, but allowing saline water to enter the lagoon.

Independent evidence for the existence of a barrier from *c.*8000 BP is provided by the study of the Sambaqui de Camboinhas (Figure 4.25), by Kneip *et al.* (1980, 1981). The midden or *sambaqui* which was built by prehistoric tool-making man (excavation of the site yielding 1062 artefacts) was found in a fossil dune 7-8 m above MSL. Five samples of mollusc shells from several levels in the midden were dated: the two oldest dates are 7958 ± 224 BP and 4475 ± 160 BP. Muehe (1982) considered the oldest date to be in error, but the evidence presented here suggests that this conclusion should be re-evaluated. It is almost certain that the mollusc shells gave ^{14}C ages which were older than the true ^{14}C ages, not least because of the delay in the transmission of carbon dioxide to oceanic water (Tooley, 1981), but the error would not be of the magnitude envisaged by Muehe. It seems reasonable that, within two standard errors, the sample should have a ^{14}C age of at least 7500 BP, and the height of the barrier suggests that it was a fossil 'Last' Interglacial barrier, similar to that discovered at Itaipu-Açu. The regressive overlap marked by the transition from clastic to biogenic deposition at the base of the peat may have been related to the formation of a Holocene barrier, in which case a barrier may have formed at Itaipú at a similar time to the first Lagoa do Padre barrier.

Between *c.* 6988 BP and 370 BP there is no clear lithostratigraphic evidence which indicated further regressive or transgressive overlaps. There is, however, biostratigraphic evidence to suggest that there are at least four transgressive episodes, separated by regressive episodes. During most of this period the lagoon was connected to the ocean by at least one tidal inlet, so the diatom death assemblage would have been markedly influenced by allochthonous planktonic marine diatoms. This makes it particularly important to consider the benthic populations as depicted in Figures 4.34b and 4.35b.

Figure 4.34b shows a rise in brackish-marine and marine-brackish taxa above the peat stratum, indicating a transgressive overlap, which culminates in a marked rise of marine-brackish *Grammatophora macilenta* var. *nodulosa* Grun.. A similar picture emerges from Figure 4.35b, but here before the rise in *G. macilenta* var. *nodulosa* Grun., there is evidence of a rise in fresh taxa (probably allochthonous, Figure 4.35c) and a decline in marine-brackish species, probably indicative of a regressive overlap. Nevertheless, the extra local nature of this evidence coupled with the fact that it only occurs at the most seaward site suggests that this is not the case. Following the peak of *G.macilenta* var. *nodulosa* Grun. there is a relative rise in the number of brackish species at both sites, indicating a regressive overlap. This is supported at Site 2 by an increase in fresh and fresh-brackish taxa, although Figure 4.35c indicates that they are allochthonous, and by a marked decrease in the marine planktonic count (Figure 4.35a). The phase comes to an end as the brackish-marine diatom count rises at both sites and there is a relative increase in the marine planktonic population indicating a transgressive overlap. Above this, an increase in brackish diatoms at both sites, this time accompanied by a rise in brackish-fresh then fresh-brackish valves, marks another regressive overlap. Evidence from Site 2 and, to a lesser extent, from Site 1 suggests that this may be interrupted by a transgressive overlap, and there is evidence of a transgressive overlap just below the surface at both sites. The latter probably occurred within the past 200-250 years as the sample from the base of the surface peat yielded a date of 370 ± 55 BP. The final regressive phase is believed to reflect the closure of the tidal inlet(s) and the sand recorded at the seaward edge of Site 2 is believed to reflect the landward migration of the barrier, possibly immediately prior to this phase.

Thus, at Itaipú, as at Itaipu-Açu, the barrier was present relatively early in the Holocene and was never breached in the way that the Lagoa do Padre and Lagoa de Guaratiba barriers were, but unlike the Itaipu-Açu barrier a sizeable inlet, or several smaller inlets existed for most of the Holocene. Figures 4.34d and 4.35d support this conclusion, with only the uppermost part of the succession showing a *Fragilaria* Lyn. presence.

5. HOLOCENE SEA-LEVEL CHANGES

5.1 Introduction

This chapter will begin with a review of the Brazilian sea-level literature. Sea-level index points from the present study, together with already published local index points will then be used to produce a time-altitude graph and to determine sea-level tendencies for Rio de Janeiro State. Barrier development between Niterói and Ponta Negra will be considered, drawing upon a range of evidence, and a new chronology of barrier formation will be produced. Modes of barrier migration will also be discussed. Finally, sea-level tendencies in other states will be determined using published data, in order to facilitate inter-regional correlation of sea-level tendencies.

5.2 A review of the Brazilian sea-level literature

Evidence for higher relative sea levels in Brazil, mainly in the form of exposed reefs, was first recognized in the nineteenth century by Hartt (1870). Nevertheless, dedicated sea-level studies, in which the principal aim was to determine the age and altitude of former sea levels, have only been carried out during the past 25 years. During the twentieth century, empirical studies relating to Brazilian sea-level change have followed one of three basic approaches: geomorphologically based, fossil based, or geomorphologically and fossil based. Only the second and third approaches have been dedicated sea-level studies. In addition, a deductive, model based approach has been tried.

5.2.1 The geomorphological approach

With the exception of the much cited early work of Branner (1904), on the sandstone reefs of northeastern Brazil, the type of study in which the geomorphological feature under investigation yields information about former sea levels can only be traced back to about 20 years before the studies which have utilized fossil data. Coastal morphological features such as exposed sandstone reefs, barrier beaches, river deltas, and terraces of various types have provided evidence for higher and lower relative sea-level stands. The most interesting works have concentrated upon sandstone reefs, wave-built terraces, erosion notches and barriers. Although these features have not been dated directly in the geomorphological studies, authors have generally presented tentative age estimates.

A sandstone reef at Pernambuco (Recife) was the first to be described scientifically; Darwin (1841) observed that the bar was lime-cemented sandstone containing shell fragments and small pebbles. Branner (1904), however, was the first to attribute an indicative meaning to sandstone reefs. The indicative meaning being the relationship of a water-level indicator to a reference water level (van de Plassche, 1977; 1986). In a study of the reefs from Fortaleza (Ceará State) to Porto Seguro (Bahia State), Branner recognized that the bedding dipped seaward at the same angle as ordinary beaches and proposed that the reefs comprised calcium carbonate-cemented beach sand. Others supported this conclusion; Tricart (1959) described the sandstone reefs as *gres de plage* and Mabesoone (1964), in a study of the reefs of Pernambuco, found roundness characteristics, surface character and structure persuasive evidence for a beach face origin, despite particle size characteristics suggestive of an offshore origin. There was, however, a different school of thought; Andrade (1955), Ottmann (1960) and Laborel (1965) all disagreed with the beach face origin. Andrade, in a study of Itamaricá Island (Pernambuco State) presumed that the reefs were cemented offshore bars, as did Ottmann who compared the calcium carbonate content of the reefs with those of adjacent beaches; sand with an equivalent calcium carbonate content to the reefs was only found in the offshore zone at a depth of 1 to 2 m. Laborel, in a study of reefs between Paraiba and Bahia States believed that the sandstone formed at the base of *restingas*, where cementation probably occurred close to the freshwater table. He observed three lines of reefs extending for hundreds of kilometres. The reefs are at +2 m, -0.5 m and -5 to -6 m with respect to hydrographic zero, in a region with a tidal range of up to 3 m.

Mabesoone (1964) cited and was presumably influenced by the work of Russell (1962), who studied beach rock in the Caribbean, Hawaii and the Mediterranean. Using x-ray analysis, Russell identified calcite cement as the primary bonding mechanism of beach rock and proposed that this cementation always occurred near the water table. He stated that:

> *"As beach rock originates only at a level approximating closely that of the strandline, it serves as an excellent guide to relationships between levels of land and sea. For the reason that it forms so rapidly it is a particularly sensitive indicator of changes of level."*

Stoddart and Cann (1965), however, showed that the primary cement of British Honduran beach rock is aragonite. This has significant implications for the indicative meaning of the sandstone reefs as its presence implies cementation in sea water, rather than close to the freshwater table. They cited Cloud (1962) who noted that aragonite is unstable and reverts to calcite when transfered from aragonite saturated salt water to aragonite undersaturated fresh water, or to moist atmospheric conditions. Thus, even if the primary cement is shown to be calcite, it could have originally been aragonite. Examples of primary aragonite cementation were quoted from many parts of the world and the authors concluded that beach rocks which appear superficially similar may have diverse origins (another case of multiple causality; see 1.2).

This uncertainty is reflected in the recent work of Muehe and Ignarra (1984). In the present study area they discovered a submerged sandstone reef which extends, almost unbroken, for about 2.5 km off Praia de Itaipu-Açu (Figure 5.1). In the west, adjacent to the Falso Pão de Açucar, it is approximately 40 m from the shoreline, about 100 m wide and 2.5 m below MSL. In the east it is 105 m from the shore, only 20 m wide and about 7.3 m below MSL. Between these extremes it is approximately 80 m from the shoreline, 30 to 40 m wide and between 4 and 5 m below MSL. The line of the reef is broken approximately adjacent to the point at which the Rio Itocáia now flows into the Canal do Costa. Despite the fact that x-ray analysis showed the cement to be calcite, the authors were aware of the possibility that it may originally have been composed of aragonite. Shoreward dipping sedimentary structures, the particle size distibution and the micro-fauna suggest that the sand was not cemented on the beach face, but in an infratidal nearshore location, possibly at the base of a barrier.

There has also been debate about the sea-level tendency - that is the dominant direction of change of sea-level movement as registered by changes in vegetation, lithology and other water-level indicators (Shennan *et al.*, 1983) - implied by the formation of a sandstone reef. Andrade (1955) and Muehe and Ignarra (1984) presumed that the reef sandstone was cemented during periods of negative sea-level tendency in a general phase of positive sea-level tendency. Clearly the submerged reef at Itaipu-Açu must have been exposed to either fresh water or the atmosphere for calcite cement to form, and the break in the reef near the present month of the Rio Itocáia suggests that the river once flowed through this gap - both of these point to a lower relative sea-level stand. Mabesoone (1964) and Laborel (1965) came to a similar conclusion, believing the rock to have formed during still-stands in a period of positive sea-level tendency. Ottmann (1960), however, believed

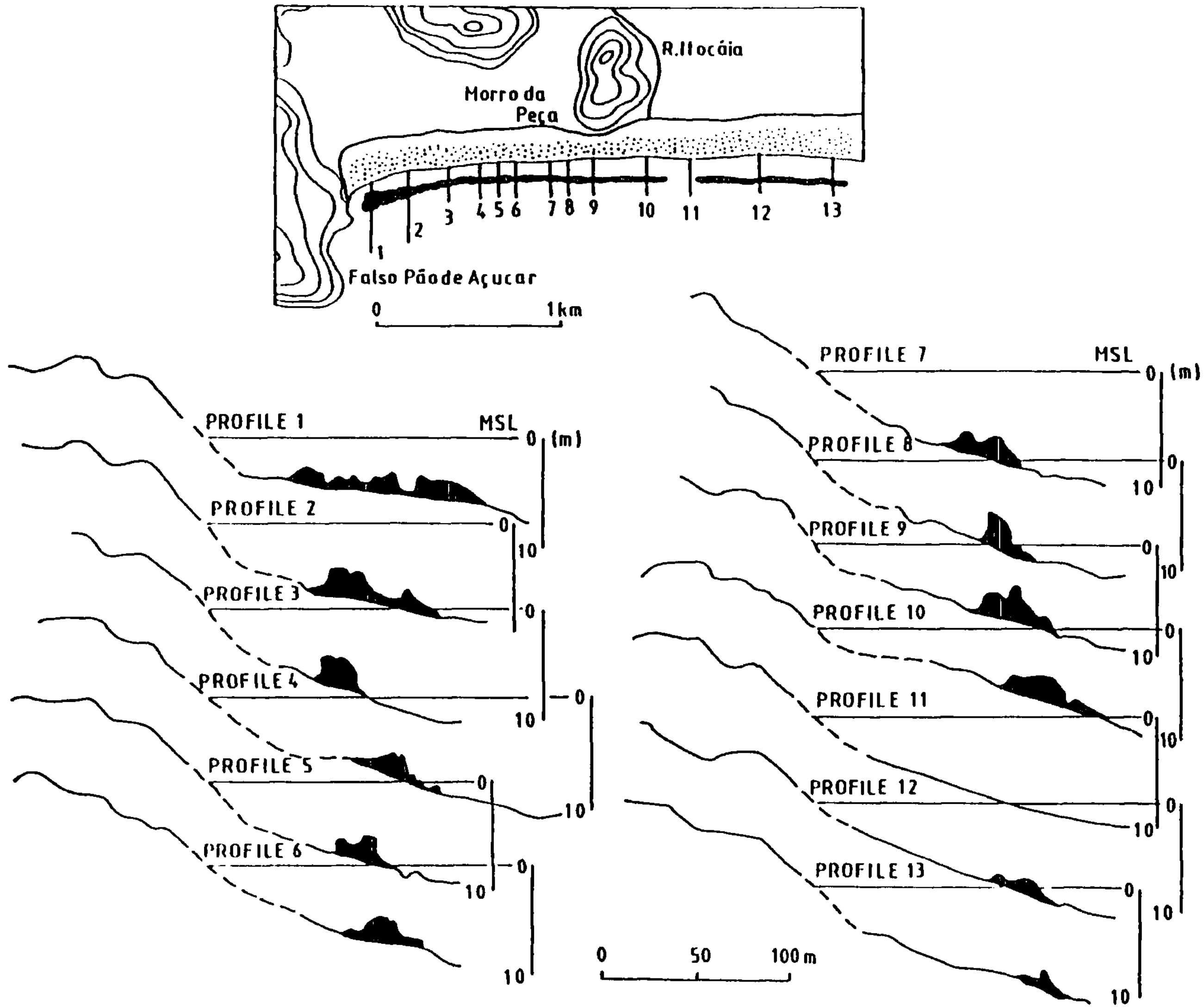


Figure 5.1 Profiles through the Itaipu-Açu beach rock, with a map showing the position of the profiles. (after Muehe and Ignarra, 1984)

that they formed in periods of still-stand during a general period of negative tendency. If reefs formed during a general period of positive tendency the ocean would expose the reef by transporting the barrier or beach sediment to the landward where another beach or barrier (and associated reef) would form; the oldest reefs would thus be to be seaward. According to Ottmann's theory the most landward reefs would be the oldest and the most seaward the youngest. Indeed, these different theories may reflect differing perceived time scales. Both theories could be correct if the former applies to a period of time equivalent to a deglacial hemicycle and the latter to the Quaternary.

Branner (1919) stated that the sandstone reefs of northeastern Brazil have been forming since the Pliocene and are still being formed. Mabesoone (1964) favoured a more recent origin for the reefs of Pernambuco, which he believed to be of Holocene age. He did concede, however, that beach rock at levels higher than the present coastline was likely to have formed during the Pleistocene. Tricart (1959), on the other hand, believed that beach rock above the present coastline could be of Holocene age; near Salvador (Bahia) formed during the late Holocene, at a time when sea level was 0.5 to 1.0 m above present MSL. Muehe and Ignarra (1984) suggested that the Itaipu-Açu beach rock formed during the late Holocene at c. 2800 BP, when the sea-level curve of Suguio and Martin (1981) indicates a regression in southern Rio de Janeiro State. A rate of landward barrier migration of 3 cm/year was then inferred. There is clearly a divergence of opinion concerning the age of the reefs, but even interpreting radiocarbon age determinations on sandstone reefs is somewhat complicated (see 5.2.3).

Few of the studies attempt to relate the sandstone reefs to a present sea level. Laborel related reefs to hydrographic zero while Muehe and Ignarra related the Itaipu-Açu reef to MSL. Assuming that MSL is 1.5 m above hydrographic zero, in the case of the reefs studied by Laborel, the reefs are

+0.5 m, -2.0 m and -6.5 to -7.5 m relative to MSL. These, however, appear to be average or estimated measurements as the work of Muehe and Ignarra showed a reef of 2.5 km in length ranging from 2.5 to 7.3 m below MSL.

In northern Brazil, on Itamaricá Island, Andrade (1955) observed raised beaches at 7-8 m and 2-3 m above present sea level. He believed these to be pre-Holocene in origin. At Rio Itaipe, north of Ilheus in Bahia State, Tricart (1959) observed terraces at 7-8 m, 5-6 m, 2 m and 1 m above present high tides. The 5-6 m and 7-8 m terraces were assumed to be pre-Holocene and the lower ones to be late Holocene in age. Tricart believed that the 2 m terrace formed prior to the formation of a barrier across the mouth of the ria and that the 1 m terrace formed is a protected lagoonal environment after a barrier had formed. Thus he implied that the same sea level was responsible. In the south, Bigarella and Andrade (1965) described wave-built terraces at 9-11 m, 5-7 m and 3-5 m along the southern coast of São Paulo State, the coast of Paraná State and the northern Santa Catarina State coast. Using a method based upon particle size and composition criteria which was developed by Bigarella *et al.* (1961), these were attributed to sea levels of 7-8 m, 3 m and 1-1.5 m respectively. They attribute all these features to the Holocene; the evidence of the Fairbridge curve (1961) suggested that sea levels reached about 3 m above present sea level and the higher terraces were explained by positive epeirogenic movements of 3-4 m. Bigarella and Andrade suggested that the terrace levels found in southern Brazil should be correlated with those found in the north.

Attempting such a correlation would require the features to be re-surveyed as there are many problems associated with the use of the published data. There has been a lack of precision in defining the reference water level, using terms such as "above present sea level" and "above present high tides" which are open to misinterpretation. The former could, for example, refer to MSL, MHW or MHWS and the latter to MHW, MHWS or to storm tide levels. The studied features could have different indicative meanings, influenced by local conditions such as the degree of protection afforded by the site and the prevalence of storms. They are undated, so those at similar altitude may not be related to synchronous changes in sea level. Also, the correction which was applied to the southern data (Bigarella *et al.*, 1961) cannot be applied to the published northern data.

Bigarella and Andrade (1965) reported the presence of erosion marks in sediments of the Barrieras Formation (Tertiary period) at 1.3-1.5 m and 3.5 m above high tide along Tibau beach on the northern coast. They believed these to be Holocene in age. Tricart (1959) also observed notches, and lines of round cupulae, along the Brazilian coastline at 3-6 m above high tide on headlands and 1 m above high tide in the more protected bays. Interestingly, even though he had attributed terraces at 2 m above present sea level to higher sea levels, he believed these to be unrelated to sea-level change. He argued that they were produced by the action of salt crystallization in the spray zone, with crystal growth in cracks weathering eventually to form notches. The elevated round cupulae were apparently an intermediate stage in this process to which reference has been made by Nunn (1984) who drew upon the work of Tricart to question the primacy of marine action in forming such notches. The exact mechanism of notch formation has never been studied, but is almost certainly related to sea level. The origin of the round cupulae is clearer and will be discussed in 5.2.2.

Muehe (1982, 1984) has been instrumental in using barriers in this geomorphological approach to sea-level study. The chronology of barrier formation developed by Muehe (1982) for barriers between Niterói and Ponta Negra (Table 5.1) was discussed in 1.1 and, as illustrated in Chapter 4, requires considerable refinement. This will be discussed further in 5.4.1.

The existing chronology does, however, have two inconsistencies: firstly the Lagoa de Piratininga barrier is at the same height as the Lagoa de Guaratiba and Guarapina barriers, but was judged to have formed 2400 years earlier when Suguio and Martin (1981) recorded a 3 m higher sea level; and secondly, while only the maximum height of waterlaid sand is recorded at all other lagoons, the Maricá barriers have been subdivided and values recorded separately for the lower eastern parts. Muehe subdivided the barriers because there is a low point approximately midway along the fossil barrier, but a borehole sunk in this depression revealed typical barrier sand which suggests that it was probably a *lido*, a feature common to most of the barriers.

Table 5.1 Muehe's (1982) chronology of barrier formation

Lagoon	Present barrier altitude (m)	Fossil barrier altitude (m)	Difference in altitude (m)	Age of older barrier in years BP
Piratininga	6.0	-	-	5100
Itaipú	7.0?	10.0-12.0?	3.0-5.0	5100
Itacoatiara	7.0?	11.0?	4.0	5100
Itaipu-Açu	7.4	12.2	4.8	5100
Maricá (west)	7.0	9.0	2.0	3700
Maricá (east)	4.0	7.0	2.0	3700
Guaratiba	6.0	-	-	2700
Guarapina	6.0	-	-	2700

In addition to developing a local chronology, Muehe (1984) marshalled evidence which indicates that the present-day barrier at Itaipu-Açu is migrating landward. The movement is believed to be in response to recent Holocene sea-level rise and to shortage of sediment supply. The presence of beach rock (believed to have formed at the base of the barrier) in an offshore position, the occurrence of cuspate spits along the seaward side of the fossil barrier yet not along the landward side of the present barrier, the pattern of sediment distribution and the erosional profile of the shoreface all points to such a landward migration. This conclusion is supported by Turcq *et al.* (1986) in their geomorphological study of the barriers between Itaipu-Açu and Ponta Negra.

Between Itaipú and the western edge of the Baía da Ilha Grande (Rio de Janeiro State) Corrêa *et al.* (1980) used a 3.5 kHz echo sounder to generate eight depth profiles across the continental shelf. When traced on detailed bathymetric charts, five distinct scarps were identified at 20-25 m, 32-45 m, 50 m, 60-75 m and 80-90 m below mean low water (MLW). These scarps were presumed to be related to ancient barrier facies which had formed during still-stands of sea level and though not dated directly, were correlated with the eustatic curve of Milliman and Emery (1968). From deepest to shallowest they were assumed to have formed at 11500 BP, 11000 BP, 10000 BP, 9000 BP and 7500 BP.

Kowsmann and Costa (1974), also working offshore, analysed 100 surface sediment samples from the north of the Brazilian continental shelf and 92 samples from the south. The percentage of terrestrially derived material in the particle size fraction over 62 μ was plotted against depth to reveal three zones rich in this material. The first was at 170 m below MLW, the second at 100-110 m below MLW and the third between -60 m depth and the shore. This material was believed to have been deposited during regressive phases, then sorted during subsequent transgressive phases. The zones were assumed to mark still-stands. On the assumption that sea level was at -130 m around 18000 BP, following Curray (1965) and Milliman and Emery (1968), two age interpretations were presented for the outer zones. The first hypothesis, favoured by the authors, called for a rate of subsidence of 3 m/1000 years for the basin, as a result of sediment loading or compaction, to explain the altitudinal discrepancy of 40 m between the -170 and -130 m levels. In this case the sea was assumed to have reached the -110 m level at 16000 BP. The alternative placed the -170 m zone at the beginning of the mid-Wisconsin transgression, 40,000 years ago and the -110 m level at 18000 BP.

5.2.2 The fossil-based approach

Van Andel and Laborel (1964), using fossil and ecological evidence, were the first to publish radiocarbon dated sea-level index points of Holocene age for Brazil. Former sea levels were reconstructed by comparing the position and altitude of living and fossil Vermetidae (worm gastropod) limestone on Cabo de São Agostinho, near Gaibú (Pernambuco State). The species composition of the fossil limestone was identical to that in the living zone; dominated by *Petaloconchus (Macrophragma)* Carpenter, probably a variant of *P. (M.) various* (Orbigny), which has a limited altitudinal range from 0.30 to 0.80 m above MLW (MSL is 1.14 m above MLW), in a well defined ecological zone. This permitted, by extrapolation, the sea level at the time of formation of the fossil limestone to be determined with an altitudinal error of ±0.50 m. The altitudinal relationships between the fossil Vermetidae, living Vermetidae and MLW were determined using a Wild level, although the position of MLW was presumably judged locally according to biological zonation, rather than by levelling to a RN.

Four large, uncontaminated blocks of limestone from 1.4, 1.6, 2.2 and 2.6 m above the living Vermetidae zone were submitted to the Shell Development Company for dating. The age determination of the highest sample of 3660 ± 170 BP showed unequivocally, for the first time, that MSL had stood considerably above present MSL during the Holocene. This was thought to be particularly significant as, being part of the Brazilian shield, Cabo de São Agostinho was presumed to be stable. A mean fall in sea level of 0.46 m per thousand years was thus indicated over a period of 2500 years.

At other locations along the northeastern coast undated fossil evidence in the form of abandoned *Echinometra* (sea-urchin) burrows well above their present life zone, fossil *Tetraclita* limestone (a barnacle which occupies the ecological zone immediately above the living Vermetidae) at approximately 2.6 to 3.0 m above MLW and beach rock 2.6 m above the present beach provided additional evidence for higher sea levels and showed that the events recorded at Gaibú were not simply local phenomena.

Hubbs *et al.* (1965) published a single date of 4800±250 BP for *Ostrea arborea* Chemnitz shells cemented to granitic rock 4.80 m above MSL and 650 m from the present coast at Grotto de Morcega, Baía da Ribeira (Rio de Janeiro State). The shells collected by Curray and Danciger are of a species believed to live in intertidal to shallow water. This altitude is thus considerably higher than the highest elevation quoted by van Andel and Laborel (1964), but as *Ostrea arborea* Chemnitz is an arboreal species which requires the stilt roots of *Rhizophora mangle* L. for its substrate, it would seem plausible that the shells cemented to granite were not *in situ*.

The research of van Andel and Laborel (1964) was extended both geographically (Figure 5.2a) and in the type of fossils dated by Delibrias and Laborel (1971) who published the dates shown in Figure 5.2b (several dates on the original time-altitude graph were incorrectly labelled, so the graph has been redrawn). These include the four dates of van Andel and Laborel (1964) (samples 3,5, 9 and 12), together with 14 new dates mostly determined by the Gif-sur-Yvette Laboratory, with a single sample from the La Jolla

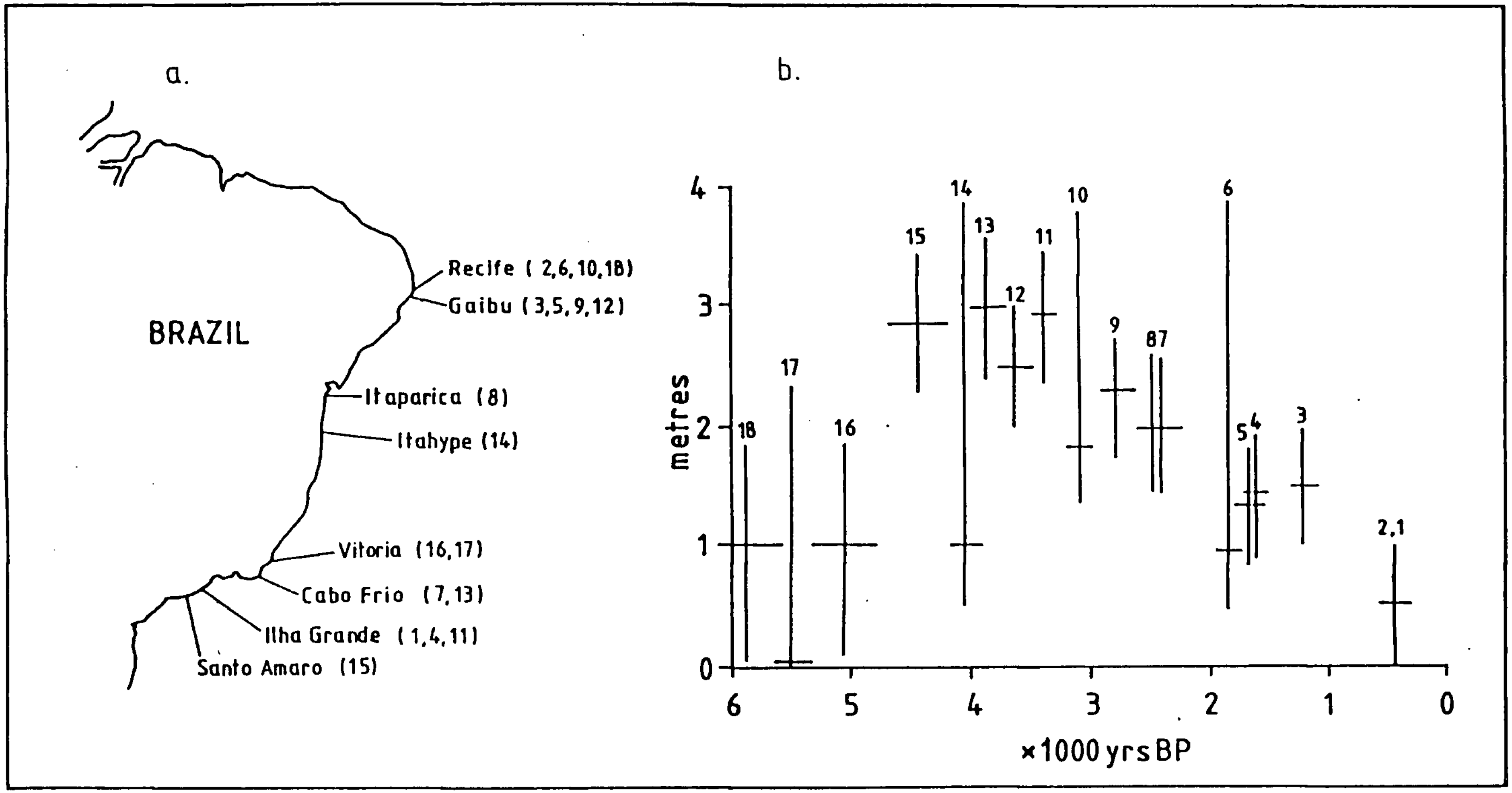


Figure 5.2 A map (a) showing the location of sites considered by Delibrias and Laborel (1971) and (b) their time-altitude diagram for the Brazilian coast. A single standard error is plotted for each radiocarbon date and an altitudinal range in metres is given

Laboratory. Most of the samples were Vermetidae limestone (samples 1, 4, 7, 8, 11, 13 and 15), but four were coral (samples 6, 10, 14 and 17), one was *'Melobesiees'* algal limestone (sample 2), one was an *in situ* oyster (sample 16) and one was *Anomalocardia* shells taken from beach rock (sample 18). Once again the altitudes were established using living homologues, as described by Laborel (1979).

The coral samples were *Siderastrea stellata* (s.6), *Montastrea cavernosa* (s. 10), *Mussismilia brasiliensis* (s. 14) and *M. hartti* (s. 16) (Delibrias *et al.*, 1971). The *Mussimilia* species are no longer found in the areas studied. Corals are difficult to use as accurate indicators of former sea levels because of their great vertical life range, a problem compounded by the lack of living homologues in the case of the *Mussismilia* sp. Delibrias and Laborel suggested that the altitudinal error was 0.5 m below the stated altitude and up to 3 m above: 2 m in the case of *Montastrea cavernosa*, 2.5 m for *Siderastrea stellata* and 3 m for *Mussismilia* sp.

The '*Mesobesiees*' algae which occupies the same life zone as the Vermetidae was attributed the same vertical error of ± 0.5 m. No taxonomic study of this group of calcareous rhodophytes has been undertaken in Brazil (Laborel, 1979). The oyster (genus not specified) was given an altitudinal error of ±1.0 m although the reason for this is not explained. Finally, an altitudinal error of ± 1.0 m was estimated for the *Anomalocardia* shells interbedded in beach rock. The authors were uncertain about the effect of cementation upon the age of the sample and felt that the shell may not be contemporaneous with the formation of the beach rock. It was not stated whether the shells were entire, assumed to be *in situ* and related to the life zone of their living homologue or whether beach altitudes were compared.

When the same dates were published in *Radiocarbon* (Delibrias *et al.*, 1971; 1974) different altitudes were quoted for three samples. Sample 4 was 0.2 m higher, sample 10 was 1.0 m higher and sample 11 was 0.4 m lower.

Delibrias and Laborel (1971) believed that the evidence collected over more than 3000 km of the Brazilian coastline showed that the events were not local, but occurred simultaneously along all of the Brazilian coast; indeed a number of samples from northeast and southwestern coasts plot very closely together on Figure 5.2b. They were, however, aware of a dated sample which was at odds with their findings. An 'unpublished' oyster date, said to be *Ostrea rhizophorae*, collected by Curray and Danciger, 4.8 m above MSL in the region of Rio de Janeiro had yielded an age of 4800 BP and it was felt that the inadequacy of *Ostrea* as an altitudinal indicator was probably responsible for the discrepancy - living *Ostrea* having been observed on Cabo de São Agostinho in wave beaten crevices 3 m above MSL. Delibrias and Laborel were clearly unaware that the shells had been taken from a very sheltered situation where this magnitude of error should not be expected, and the hypothesis proposed earlier seems to provide a more likely explanation.

Fairbridge (1976) modified his global sea-level curve (Fairbridge, 1961) using fossil evidence from Brazil (Figure 5.3). 28 Brazilian sea-level index points were plotted, together with elevation minima for 28 dated allochthonous fossil shells from *sambaquis* (11 from Paraná State and 17 from Santa Catarina State). Four major transgressive stages were identified (the Older Peron, Younger Peron, Abrolhos and Rottnest of the 1961 curve) separated by three regressive stages. It is clear from Figure 5.3, however, that the Brazilian evidence plotted around the new curve only corroborates the first of these regressions (his Bahama Emergence). Nevertheless, following Bigarella (1965), the first three transgressive stages were given

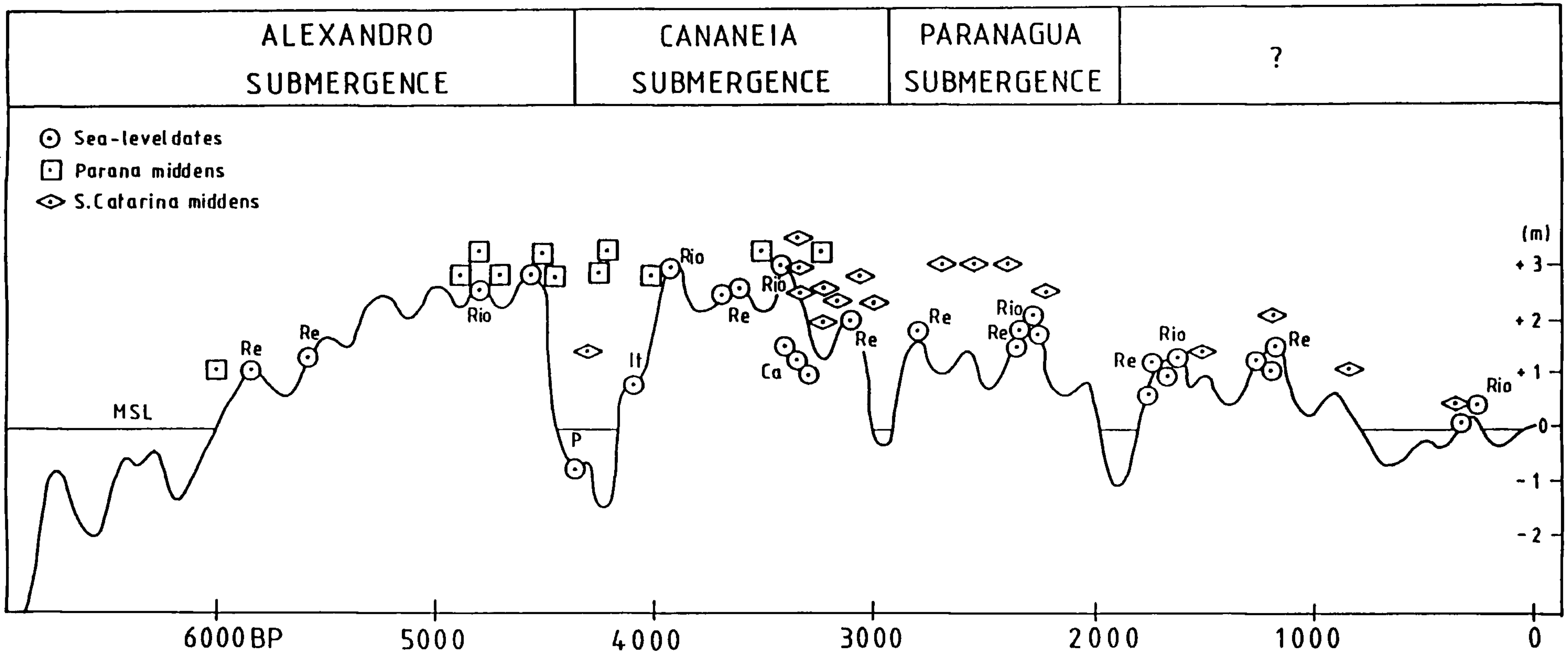


Figure 5.3 Fairbridge's (1976) Sea-level curve incorporating Brazilian data. (Re = Recife, Rio = Rio de Janeiro, P = Paranaguá, It = Itahype, Ca = Carniça)

local Brazilian names - the Alexandro Submergence, the Cananéia Submergence and the Paranaguá Submergence - while the fourth remained unnamed. This is significant because Bigarella recognized only three transgressive stages, which due to the lack of Brazilian sea-level dates he suggested might relate to the Fairbridge Stages. The 9-11 m Alexandro wave-built terrace, which Bigarella suggested could have formed during the Older Peron, is almost certainly pre-Holocene in age which leaves only two possible Holocene transgressive stages. Fairbridge presumably did not consider the link between terrace elevations and the usage of the local names to be important, as he stated that all three wave-built terrace levels probably formed during the previous interglacial.

The sea-level index points used by Fairbridge were taken from the work of van Andel and Laborel (1964), and Delibrias and Laborel (1971), supplemented by dates on *in situ Anomalocardia* shells collected by Fairbridge from the sands of a marine spit at Carniça (Santa Catarina State). There are, however, two discrepancies: firstly, several unattributed index points are plotted on the graph and secondly, the index points are frequently inaccurately plotted and as a consequence lie closer to the curve. The Paranaguá index point is a *Sambaqui* date so there are 27 Brazilian index points on the graph. Van Andel and Laborel, and Delibrias and Laborel published 17 of these (one of their points not being plotted) and up to three are from Carniça (in one part of the paper Fairbridge stated that two shells were collected), which leaves seven unattributed index points. Two of these (dated 2550 ± 110 BP and 2460 ± 110 BP) were incorrectly attributed to Delibrias and Laborel and the remainder were not explained. The second oldest index point plotted on the graph provides an example of plotting inaccuracy; it is approximately 1 m too high. There are also at least six other points which have been inaccurately plotted and the Delibrias and Laborel index point which was not included would lie over 1.5 m below the curve.

Fairbridge and Richards (1970) suggested that phases of abandonment should be related to transgressive stages and phases of occupation to regressive stages, but, despite restating this approach, Fairbridge (1976) did not utilize the midden evidence in this way. Instead, dated altitudes were plotted as minimum elevations. In principle this is less useful as the middens do not have a fixed relationship to any reference water level - Fairbridge commented that once established the middens tended to be maintained, even if it meant climbing 10 to 20 m with every basketful of shells. Perhaps only elevations were plotted because the relationship between occupation, abandonment and sea-level change was more complicated than originally proposed. Indeed, during the Alexandro Submergence middens appeared extensively in Paraná and are common is successive transgressive stages, while during the Bahama Emergence the middens around the Baía da Antonina (Paraná State) were abandoned, apparently because the sites became isolated from the ocean.

The approach adopted by Fairbridge is not to be favoured, irrespective of the inherent discrepancies, as it is undesirable to relate Brazilian index points to a curve generated using index points from many different parts of the world, not least because the isostatic responses of the different land masses to Holocene sea-level rise have varied greatly.

Cunha (1977) recorded the presence of fossil sea-urchin burrows along the Atlantic coast in the vicinity of Baía de Guanabara (Rio de Janeiro State). These burrows, described by Laborel (1979) as round cupulae in hard crystalline rock, are presumed to have been formed by the rock-burrowing *Echinometra lucunter*, the dominant present-day species. They are 6 to 8 cm in diameter and 12 to 16 cm deep. Cunha determined the altitude of the fossil burrows with respect to MLW by first measuring their height above the actual tidal level, then using tidal tables to establish the predicted height of the tide above MLW at the time of measurement. This is an unfortunate method as, in addition to meteorologically induced uncertainties, the fossil burrows were not compared directly with the zone occupied by living *Echinometra* so that no account was taken of the varying energy environments encountered along this coast, where the urchins will live considerably higher on exposed headlands than in the sheltered bays. Living *Echinometra* were simply assumed to occupy burrows at, or below MLW. Burrows, which obviously cannot be dated directly, were observed 2 m below MLW at Copacabana and up to 1.4, 2.1 and 6.4 m above this level at Mambucaba, Arpoador and Itacoatiara, respectively. Interestingly, these are the same features described by Tricart (1959) and attributed to salt weathering. The conclusion, reached by Tricart, that such features do not indicate former sea levels is clearly erroneous.

5.2.3 The geomorphological and fossil-based approach

The first sea-level curve was not produced using this approach until 1975, but the use of the general principles can be traced back to the early 1960s when J.J. Bigarella collected a piece of wood from an ilmenite layer under 1.8 m of old beach deposits in the Baía de Paranaguá (Paraná State). This was submitted to Isotopes Inc. for dating by W.R. Hurt, of the University of Indiana, who suggested that the beach deposits overlying the specimen may correspond to the worldwide rise in sea level designated the Abrolhos (2800-2100 BP) by Fairbridge (1961). This opinion was supported by the radiocarbon age determination of the wood of 2675 ± 150 BP (Trautman and Willis, 1966). This index point is clearly not of the same quality as the dated Vermetidae limestone because the wood is not *in situ* and there is the possibility of a time lag between its burial and the deposition of the beach sand. However, as the layer is 0.8 m above the present MHWS and is overlaid by 1.8 m of sand, a MHWS approximately 2.6 m higher than the present shortly after 2675 BP could be inferred. This is in broad agreement with the Delibrias and Laborel (1971) evidence.

Kneip *et al.* (1975) working on the Sambaqui do Forte, which is situated on a small crystalline knoll adjacent to the town of Cabo Frio (Rio de Janeiro State), used an approach similar to that recommended by Fairbridge and Richards (1970). Two periods of occupation, separated by an abandonment phase, were identified; the periods of occupation being interpreted as regressive stages and the period of abandonment, during which the site was covered with blown sand, as a transgressive stage. The authors believed that abandonment coincided with a rise in sea level that turned the site into a small island, but the sand-blowing phase could equally be related to a regressive stage, when a greater area of sand would be exposed to wind action. Independent evidence for a higher sea level was provided by sea-urchin burrows, which indicated a rise of up to approximately 4 m above present levels. The most elevated burrows are, however, not very distinct and the possibility that they were formed during a previous interglacial should be considered. No dates were available for the *sambaqui* at this time, but later, Pallestrini and Kneip (1979) reported the results of radiocarbon age determinations on molluscs from the lower and upper *sambaqui*. The age of the top of the lower midden, where there is an erosional contact with the overlying sand, is 5520$\pm$120 BP and the age of the base of the upper midden is 4330$\pm$140 BP. These dated levels clearly cannot be used as sea-level index points because the relationship between the midden and a reference water level cannot be determined and there is uncertainty about the sea-level tendency implied by abandonment.

To the west of Cabo Frio, within Baía de Guanabara, Cunha and Andrade (1977) studied the back beach sediments of Praia das Flechas (Niterói) and fossil sea-urchin burrows on an adjacent gneissic cliff. A marine deposit of well rounded quartz sand with some boulders over 0.5 m in diameter was found, the top of which lies from 2.55 m to 3.05 m above present MHW. It was believed to comprise fluvial sediment that had been eroded, reworked and redeposited by the sea. On the neighbouring rockface, fossil *Echinometra* burrows were discovered 2.70 m above the zone now permanently occupied by adult sea-urchins. The work produced no index points as no datable material was found, but the evidence was assumed to mark the maximum altitudinal extent of the Holocene transgression in this area.

Since the mid 1970s, in cooperation with the Office de la Recherche Scientifique e Technique Outre-Mer (ORSTOM), a group of Brazilian and French scientists from the Universidade de São Paulo, the Universidade Federal da Bahia and the Observatório Nacional have produced over 70 publications relating to Brazilian sea-level fluctuation. In fact over this period virtually all studies of Holocene sea-level changes along the Brazilian coast have been carried out by this group. Some of their most important works, which describe the sea-level index points they have identified and illustrate the geomorphological and fossil based approach they have adopted, will be discussed here.

Such studies were initially confined to the Cananéia-lguape coastal region of São Paulo State (Martin and Suguio, 1975; 1976) but were extended to the whole of this state and to the southern Rio de Janeiro State coast shortly after (Suguio *et al.*, 1980 - presented at the 10th INQUA Congress, Birmingham, 1977). This work was expanded upon during the International Symposium on Coastal Evolution in the Quaternary, São Paulo in 1978

(Martin *et al.*, 1979a) where the first index points and curve for Bahia State were also presented (Martin *et al.*, 1979). In the following year, the coastline of southern Rio de Janeiro State was subdivided and more index points were presented for the State of Bahia (Martin *et al.*, 1979-80). More recently (Martin *et al.*, 1985; Martin and Suguio, 1986) the States of Paraná and Santa Catarina have been the subject of study. In the earliest papers index points were described in some detail but in the later works, when most of the radiocarbon dates were published, only the types of dated material and the indicative meanings were provided, making it difficult to assess the quality of the majority of index points. It is possible, however, by considering the merits of the different types of dated material and of the general approach used, and by examining the more detailed evidence presented in the earlier papers, to judge the accuracy of the published data.

A relatively large number of index points has been identified using several types of fossil and geomorphological evidence. The fossil evidence was subdivided into primary, geological evidence in the form of plant and animal fossils and secondary, archaeological evidence in the form of *sambaquis*. *Sambaquis*, which are most common south of Rio de Janeiro State, have been used by this group as evidence of sea-level change to supplement geological evidence in all studied areas south of Santos (São Paulo State) and to a lesser extent in Bahia State. The fact that it is not possible to establish an altitudinal relationship between the *sambaqui* shells and a reference water level was accepted but, as the Indians must have tipped their shell debris on mounds above MHWS, they were considered valuable when used in conjunction with other evidence. If evidence from *Sambaquis* is to be used, however, it is important to obtain a series of radiocarbon dates, preferably both vertically and horizontally, through each mound in order to generate age profiles and identify age anomolies. This has seldom been carried out and a single age determination on shells taken from near the base of the midden's edge has generally been used to date the initial occupation of the site. Such an approach cannot produce accurate results as these mounds have developed from small nuclei into large mounds containing up to 120000 m^3 of shells (Fairbridge, 1976), making it difficult to locate a mound's nucleus or, if a large mound has formed from the merging of several formerly distinct mounds, a mound's nuclei. Considerable variation would be expected along an age profile through the base of a *sambaqui* with shells getting progressively younger away from the nucleus, but with age reversals resulting from slumping and gaps in the time series as a consequence of abandonment and reoccupation of the site.

A dated *Ostrea* shell from near the base of the Sambaqui de Rio Boguaçu, one of the four *sambaquis* used on the construction of the first Cananéia - Iguape curve (Suguio and Martin, 1975) illustrates the problem. It was not possible to establish the height of the midden directly because it was situated in a closed forest, yet its base was presumed to be 2.1 to 2.6 m above MSL and used to indicate a sea level higher than the present when the site is relatively close to a mangrove swamp from where oyster shells could have been collected (the species of *Ostrea* is not specified). In addition, a negative sea-level tendency was inferred from the fact that the *sambaqui* site had been occupied (occupation = negative tendency, abandonment = positive tendency). The validity of this assumption has already been questioned in the discussion (5.2.2) of Fairbridge's (1976) paper. Finally, the shell was not taken from the nucleus of the mound, so the age of the initial occupation pre-dates the published radiocarbon age.

Dates on fossil wood have been used quite extensively, particularly in São Paulo State, to determine the age of sea-level stands, but on only one occasion was the wood *in situ* - a tree trunk in growth position covered by shallow marine sands. Wood samples were mostly taken from argillaceous or arenaceous deposits and an indicative meaning applied to these deposits. The authors argued that if the material had not been buried quickly it would have rapidly decomposed, but the possibility of secondary deposition should not be ignored. Plant detritus was only dated at one site, where it was found to be covered by sand displaying sedimentary structures characteristic of the beach face. Similar concentrations of detritus were found to be forming on the present-day beaches in the area and so the material was assumed to have been deposited on the foreshore near the berm crest.

Both autochthonous and allochthonous shells have been used very widely. Worm gastropods and oysters, both of which were discussed in 5.2.2, are the most frequently used *in situ* fossil shells. The Vermetidae evidence of Delibrias and Laborel (1971) and the *Ostrea* samples submitted for dating by Curray and Danciger (Hubbs *et al.*, 1965) have been incorporated. Other *in situ* shells were used but the genus, if known, was not specified making it impossible to assess their value as index points. The allochthonous shell types were also not described compounding the limitations which are inherent in using them as index points. The shells themselves cannot be compared with modern homologues and detailed micropalaeontological and sedimentalogical analyses would be required in order to determine accurately the depositional environments. Shells from beach rock have been used, particularly in Bahia State, although the type of analysis which was carried out on the sandstone to determine its beach-face origin was not discussed and the shells were not described as being *in situ*. Flexor and Martin's (1979) paper does imply that particle size and structural characteristics were analysed, but reference to beach rock samples by Bittencourt *et al.* (1979) suggests that the shells were allochthonous and not always fresh and unaltered. When both the shells and the cement were dated for four beach rock samples considerable age discrepancies resulted. The mean of the age discrepancies between shells and surrounding cement was 3301 years (Flexor and Martin, 1979). Corals of unspecified type have been used to indicate minimum altitudes in Bahia State - an upper limit was not determined because, as indicated in 5.2.2, corals have a great vertical life range. Unfortunately, the question of whether there are living homologues of the dated corals (Delibrias and Laborel; 1971) cannot be addressed.

Geomorphological evidence takes the form of wave-cut and wave-built terraces, with up to three distinct terrace levels having been identified within a single coastal region (terraces which Fairbridge, 1976 considered to be pre-Holocene). As with much of the other evidence detailed descriptions are confined to the earliest works, so the terraces of the Cananéia-Iguape region (Martin and Suguio, 1975) will be considered here.

On Ilha Comprida the Cananéia Formation has been cut by wave action to a level 2.5 to 3 m above MSL, while to the landward on Ilha de Cananéia the Formation is 5 to 6 m above MSL. This discrepancy was attributed to the erosive action of the sea when it stood at least 3 m higher than the present. The date obtained on shells collected from the lower part of the Sambaqui de Rio Nóbrega, which was built on this wave-cut terrace provides a minimum age of 4380 ± 340 BP. It should be noted, however, that the spatial extent of the wave-cut terrace is relatively restricted, extending over the entire width of the southern end of Ilha Comprida but not affecting the Cananéia Formation in the north of this island or on Ilha de Cananéia. This does not appear to be compatible with the hypothesis that sea-level stood at least 3 m higher than the present along this coastline, as such a level should have affected the Cananéia Formation in all areas. Rather it points to a localized event which occurred at some time prior to 4380 BP. The wave-built terrace formed from reworked Cananéia Formation sands, reaches a maximum altitude of 3 m above present MHW and was dated using the plant detritus, described above, which was found at its base. There is no dated material to indicate a minimum age for the terrace.

The altitudes of sea-level indicators were determined with reference to local tide levels by comparing the ancient sediments or fossils with modern homologues. The type of instrument used to fix the altitudes is not described and it is by no means certain that an accurate level would have been used. The Departmente de Geografia, Univeridade Federal de Rio de Janeiro, for example, did not possess such an instrument. No attempt was made to relate the altitude of index points to the national datum, nor indeed to any common datum, so it is impossible to reassess the indicative meaning of the collected samples. In the case of *in situ* fossil Vermetidae limestones the adopted approach is generally assumed to give rise to few problems (see 5.3.1.1) thanks to the restricted niche occupied by this family of gastropods and the nature of the substrate to which they attach themselves. Indeed, where there are no living Vermetidae it is still possible to use this approach by comparing the fossil gastropods with the base of the zone occupied by the barnacle *Tetraclita*. Where allochthonous material, in the form of shells and wood fragments, has been taken from argillaceous lagoonal sediments the situation is far more complex and problematic. Possibly the most fundamental problem is that there are frequently no modern lagoons with which to compare the ancient deposits, but in addition the depth of water in which the dated materials were deposited is unknown, it is not clear whether the former lagoons were isolated from or open to the sea (although Martin *et al.* (1979-80) attempted to use the $\delta^{13}C$ (PDB) values of the $^{13}C/^{12}C$ ratio for dated *sambaqui* shells to indicate changes in lagoonal salinity regimes in the Cananéia-lguape region, see also Martin *et al.* (1986)), nor is the degree of compaction which may subsequently have occurred considered. This is a serious weakness in a methodology which relies so heavily upon time-altitude relationships.

Confidence in the indicative meanings of many of the samples is further undermined by the fact that different altitudes (and confidence limits) have been quoted for the same sample in different publications. This can be illustrated using two dated allochthonous wood fragments from mangrove formations: sample A93 was described at the 10th INQUA Congress in 1977 (Suguio *et al.*, 1980) as being 1.1 (±0.3) m below its present day homologue, while in 1979 (Martin *et al.*, 1979-80) it was only 0.4 (±0.4) m below this level; sample A55 was first reported to be 0.8 (±0.2) m above its modern homologue by Martin and Suguio (1976) yet Martin *et al.* (1979a) stated that it is 1.2 (±0.4) m above its homologue. This is a relatively widespread phenomenon, even applying to some Vermetidae samples, with 24% of the São Paulo State index points having changed altitude.

Unfortunately this problem of inconsistency in published data is more widespread. Different ages have been attribute to samples dated at the Laboratório Física Nuclear Aplicada, Universidade Federal da Bahia, when exactly the same laboratory code has been used. This is true of 39% of the dated samples for São Paulo State. For example, the age of sample A254 (Bah 354), a Vermetidae limestone, has been quoted as 4760±110 BP (Suguio *et al.*, 1980) and as 5010±120BP (Martin *et al.*, 1979a; Martin *et al.*, 1979-80). Sample A291 (Bah 453), an oyster, was quoted as 640±80 BP (Suguio *et al.*, 1980) and as 885±115 BP (Martin *et al.*, 1979a; Martin *et al.*, 1979-80).

Another significant weakness with this approach to sea-level study is the use of isolated index points, where the lack of other dated samples in the same stratigraphic sequence and of detailed litho- and/or biostratigraphic analysis leads to the use of erroneous data in the construction of sea-level curves. This point can be illustrated neatly using sample A263, a beach rock shell taken from 4.2 m above MSL, which yielded a radiocarbon age of 3480±70 BP (Bah 355) and was used in 1977 by Suguio *et al.* (1980) as a key maximum turning point in the sea-level curve for the Bertioga region of São Paulo State (Figure 5.4.g). In 1978, however, Martin *et al.* (1979b) obtained an age of 5470±100 BP (Bah 609) on shell debris 2.7 m below the beach rock and, as lithostratigraphic evidence indicated that both samples were deposited during the same transgressive phase, sample A263 was presumed to have been rejuvenated. An assumption which was supported by the $\delta^{13}C$ values of the $^{13}C/^{12}C$ ratio (with respect to the PDB standard) which showed that the beach rock shell had been contaminated by continentally derived carbon. Martin *et al.* (1979b) rejected two other index points, but other isolated index points could be similarly affected.

Since 1976 sea-level curves have been published for 11 coastal units, although only eight curves have been included in recent publications (Martin *et al.*, 1985; Martin and Suguio, 1986). The curves, illustrated in Figure 5.4, appear superficially very similar, displaying three transgressions in Bahia State and two, or possibly three transgressions in other states. This similarity has, however, arisen at least in part because of the way the curves have been plotted. Only those representing the coastal area north of Salvador (Figure 5.4a) and the Santos area (Figure 5.4h) pass through the majority of index points and are well defined by those index points. The others have simply been drawn to follow a similar pattern.

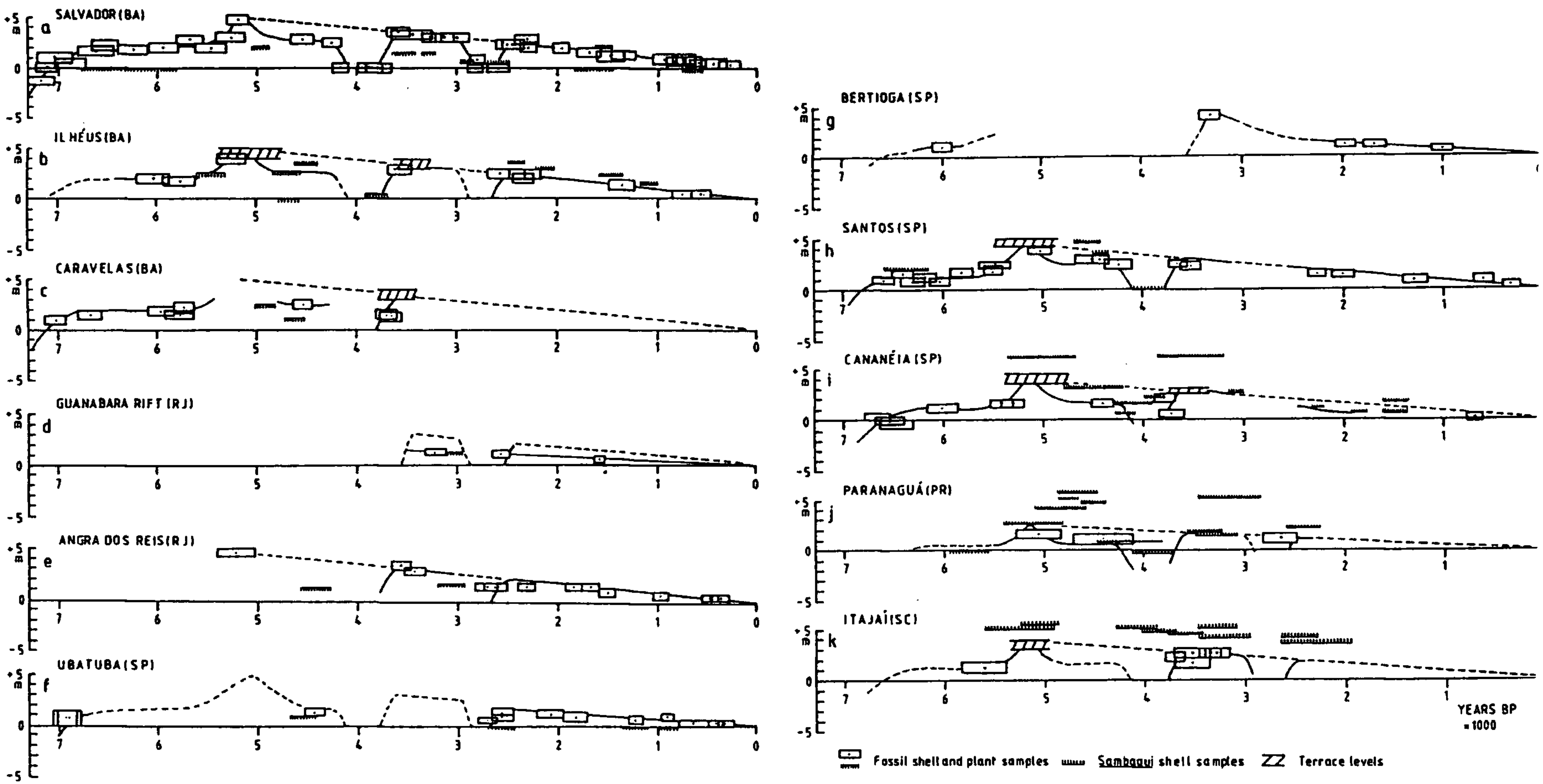


Figure 5.4 Sea-level curves produced by the São Paulo/Bahia/ORSTOM group

Despite the limitations of the approach, altitudinal discrepancies between the curves at *c*.5150 BP were considered to be significant and explanations were sought to account for them. Following Mörner (1976), Suguio *et al.* (1980) and Martin *et al.* (1979-80) attributed apparent anomalies of up to 1.5 m between regions to changes in the geoid surface during the Holocene. This surface, which over the seas coincides with MSL (+ 1 m) (Jardine, 1986), is characterized by highs and lows of as much as 170 m in amplitude at present and corresponds to an equipotential surface of the earths gravitational field. It is controlled by rotational and gravitational forces acting upon the globe (Mörner, 1980). The importance of the Brazilian data was recently emphasized by Nunn (1986) who, using the work of Suguio *et al.* (1980) as an example, stated that the evidence for geoidal eustasy is largely inferential and dependant upon either disparities in the data used to identify former sea levels, or inconsistencies between model predictions and "observed" shoreline changes.

The geoidal-eustatic change hypothesis was developed by Martin *et al.* (1985) incorporating the newly acquired Paraná and Santa Catarina State data which gave rise to a maximum inter-regional discrepancy of 2.7 m at *c.* 5150 BP (Table 5.2). Terraces mark the *c.* 5150 BP maximum in all chosen regions except Angra dos Reis where a dated *Ostrea* shell collected and submitted for dating by Curray and Danciger was used. Two samples from the same altitude yielded ages of 5200±200 and 4800±200 BP and although both dates were used in early publications, Martin *et al.* (1979-80) discounted the younger sample. No concern was expressed over the quality of the index point yet, as the problems attributed to the younger sample (see 5.2.2) also apply to this one, it cannot be considered to be reliable. It has not been possible to assess the quality of evidence afforded by most of the terraces, but the validity of the interpretation of the Cananéia terrace evidence was questioned above. The age of the terrace (based on a single *sambaqui* shell date) cannot be accurately ascribed to 5150 BP and when first described (Martin and Suguio, 1975) the terrace was 3.0 m above MSL, not 3.5 to 4.0 m as described by Martin *et al.* (1985) (Table 5.2). In addition, it should be noted that in the vicinity of Paranaguá (Paraná State) Martin *et al.* (1985) identified sea-level maxima of 2.3 m above MSL at 5150 BP and of 1.6 m above MSL at 3600 BP, yet the data collected by Bigarella (Trautman and Willis, 1966) indicated a sea-level maximum of 2.6 m shortly after 2675 BP.

Table 5.2 Maximum Holocene sea-level altitudes for different coastal regions of Brazil, after Martin *et al.* (1985)

Brazilian coastal sector	Altitude of maximum sea level *c.* 5150 BP (in metres)
Salvador	5.0
Ilhéus	5.0
Caravelas	-
Angra dos Reis	4.8
Santos	4.5
Cananéia	3.5-4.0
Paranaguá	2.3
Itajaí	3.5

Martin *et al.* (1985) assumed that the post 5150 BP emergence of the coastline resulted from subsidence in the geoidal relief and that the altitudinal descrepancies between regions could be explained by migration of the geoid relief. Using the geoid surface shown in Figure 5.5, which was produced using the GEM-10-B model transformed to fit the Brazilian geodetic system using 120 Doppler control points, it was determined that a slight displacement of the central axis in a WSW to ENE direction would

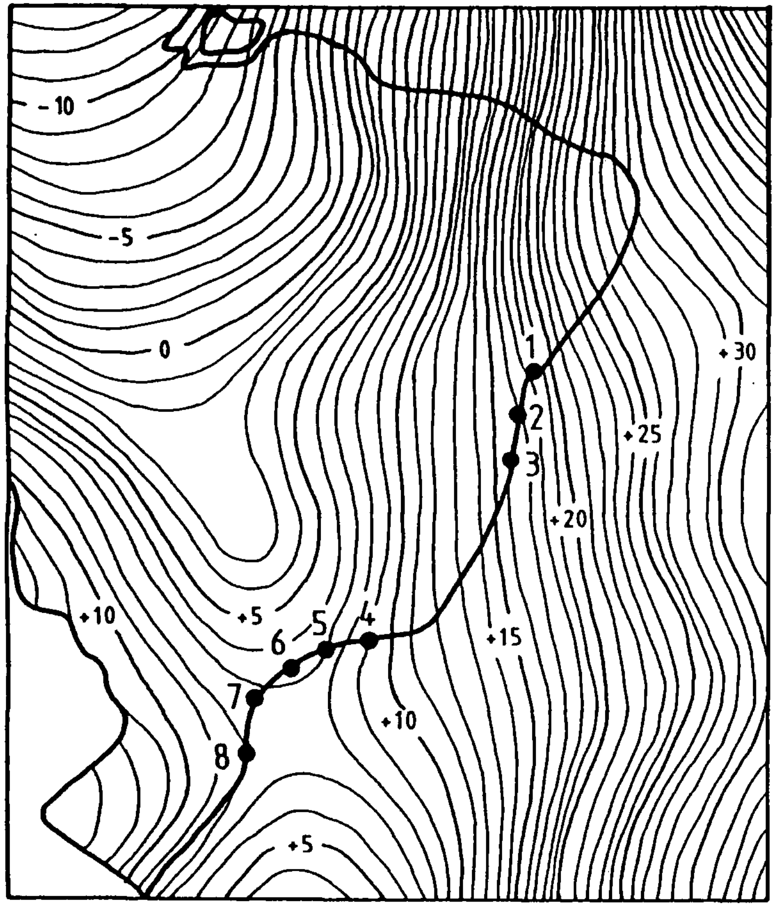


Figure 5.5 A map of the geoid surface (1 = Salvador, 2 = Ilhéus, 3 = Caravelas, 4 = Angra dos Reis, 5 = Santos, 6 = Cananéia, 7 = Paranaguá and 8 = Itajaí)

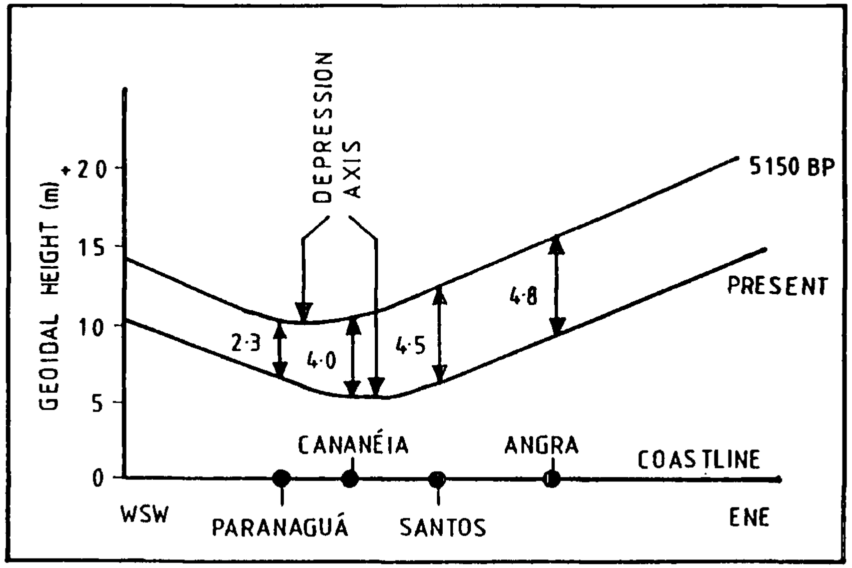


Figure 5.6 The graph of Martin *et al.* (1985) showing the comparison of the present geoidal surface with that of 5150 BP between Angra dos Reis and Paranaguá

explain the shifts observed between Angra dos Reis and Paranaguá (Figure 5.6). The geoid surface is of course related to MSL-Imbituba while the sea level measurements are not. Differences of the right order would result from such a shift when combined with subsidence of 3.0 m over the period, although approximately 0.5 m less emergence would result in Angra dos Reis. There would, however, be 1.0 m too little emergence at Itajaí (Santa Catarina State) and on the coast of Bahia State - where there is no observed discrepancy and where the authors predicted no change would result from geoidal displacement - an altitudinal anomaly of 0.5 m would have resulted between Ilhéus and Salvador. In addition, a similar rate of geoidal subsidence would have produced emergence of between 5.5 and 6.0 m rather than the observed 5.0 m.

The same displacement and subsidence of the geoid would probably not be expected in Bahia and São Paulo because of the complex relationship between geodial change and mass redistribution, but if a similar change was predicted between Paraná State and Rio de Janeiro State, Santa Catarina State should have been similarly affected. Furthermore, even if it is assumed that the geoid did not respond in a uniform way and that there was a more marked shift in São Paulo State, the closeness of the isobases in Bahia State would probably still have produced anomolies between neighbouring coastal units. These inconsistencies and the uncertainties surrounding the evidence used to indicate altitudinal anomalies must, therefore, cast doubt on the hypothesis that geoidal migration explains altitudinal discrepancies of former sea levels along the Brazilian coast. This is not to say that the hypothesis should be rejected, but simply that the evidence available does not allow its rigorous testing.

Martin *et al.* (1979-80) subdivided southern Rio de Janeiro State into three units; the first was within Baía da Ilha Grande (Parati-Angra dos Reis)

(Figure 5.4e), the second was within the rift zone of Baía de Sepetiba (Figure 5.4d) and the third was between Sepetiba and Barra de Guaratiba at the eastern, seaward edge of Baía de Sepetiba. The index points within the rift zone were considered to be at lower altitude than those of Baía da Ilha Grande and thus to indicate Holocene tectonic activity within the Guanabara Rift. As discussed in 1.2, Almeida (1976) stated that the Rift may still be active, but also considered that it could extend to include Baía da Ilha Grande, in which case differential emergence would not be expected. When all the Ilha Grande index points are plotted (Figure 5.7a) (six index points which lie between Parati and Angra dos Reis were not included on the original curve, despite having been published the previous year) and the three index points which lie between Sepetiba and Barra de Guaratiba are included (Figure 5.7c) it should be apparent that there is no evidence to support decreased rates of emergence in what Martin *et al.* (1979-80) considered to be the Rift (Figure 5.7b). The evidence does, however, suggest that the sea-level curve of Martin *et al.* (1979-80) is in error (Figure 5.7d). There is no evidence to suggest that sea level was below its present level at *c.* 2700 BP and a more rapid regression is implied at *c.* 3400 BP.

During this period when the São Paulo/Bahia/ORSTOM group have been studying sea-level changes close to the present coastline, others have been working on Late Glacial and early Holocene sea-level changes, as reflected by geomorphological and fossil evidence found on the continental shelf.

In an extension of the work carried out by Kowsmann and Costa (1974), which was discussed in 5.2.1, Kowsmann *et al.* (1977) studied the continental shelf between Santos (São Paulo State) and the southern border of the State of Rio Grande do Sul. They combined the analysis of all the available bottom penetrating 3.5 kHz echo-sounding records with lithological and micropalaeontological analyses and radiocarbon dates obtained from 20

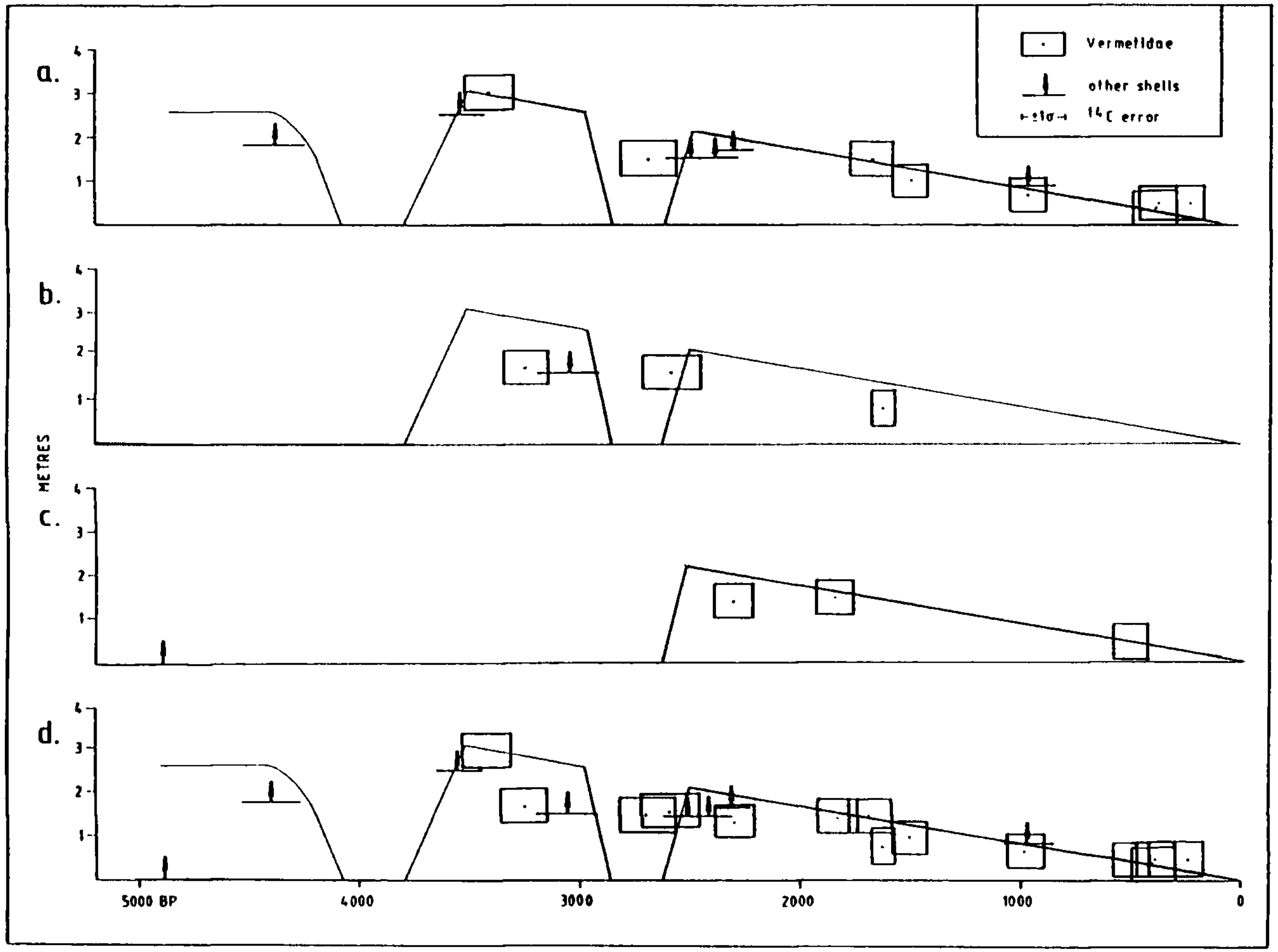


Figure 5.7 Index points from Baía da Ilha Grande and Baía de Sepetiba (taken from Martin *et al.*, (1979-80) for (a) Parati to Angra dos Reis (b) the Guanabara Rift (c) Sepetiba to Barra de Guaratiba and (d) the area as a whole

piston cores. Sediment rich in broken mollusc shells was found to be concentrated on the outer shelf at about the 130 m isobath - the presence of coastal benthic foraminifera and coarse continentally derived sediment led them to conclude that it was a shoreline lag deposit. A radiocarbon date yielded an age of 17420±270 BP, although the samples could have been contaminated by the reworking of older shells. Most of the remainder of the shelf appeared to be sand covered with a homogeneous mud facies lying over the sand, or directly over Pleistocene sediments in the middle shelf. The sand was assumed to have been deposited in shallow water as the shoreface retreated in response to sea-level rise, while the mud was believed to have been deposited later, in deep water. Two scarps, corresponding approximately to the present 60 and 110 m isobaths, were identified in the sand substrate and presumed to be remnants of beach ridges formed during periods of still-stand then partially destroyed and drowned as sea-levels continued to rise.

Nine radiocarbon age determinations, predominantly on shells, were carried out by Professor Valastro of the University of Texas and used with two dates obtained by Figueiredo (1975). As Table 5.3 shows, however, there is great divergence in the age of deposits from approximately the same depth. In an attempt to resolve this problem Kowsmann *et al.* (1977) plotted the dates against the Milliman and Emery (1968) eustatic curve and showed that older deposits were likely to have been laid down during a mid-glacial regression, while the younger sediments, from the same depth, were probably deposited during the post-15000 BP transgression. Dates which did not lie close to the curve were thought to be contaminated. Despite the fact that Thom (1973, p 186 and 190) largely discredited the Milliman and Emery curve, he marshalled evidence from around the world that pointed to sea levels attaining altitudes of 30 m below present sea level at around 35000± 10000

BP, so this hypothesis remains to be refuted. Assuming the hypothesis to be correct, the age of the -110 m scarp would be *c.* 13000 BP. The authors corrected the date of the -130 m still-stand to 15000 BP using the Milliman and Emery curve. The possibility of much more widespread contamination should not be ignored.

Table 5.3 Radiocarbon dates from the south of Brazilian continental shelf after Kowsmann *et al.* (1977), Figueiredo's (1975) samples are marked with an asterisk.

Sample depth (m)	Material	^{14}C age $\pm$ 1σ BP
19	surface shells	6470±70
25	surface shells	21110±430
28*	surface beach rock	16250±1670
28	surface shells	23050±550
40*	surface shells	17000±340
100	subsurface shells	14690±170
105	subsurface shells	12550±140
115	subsurface shells	19910±330
132	subsurface calcareous algae	17330±480
135	surface shells	17420±270
136	surface shells	13780±170

The Albrolhos continental shelf which lies between Carvelas (Bahia State) and Regencia (Espírito Santo State) is relatively wide and shallow with an extensive depression; the Depressão de Albrolhos. Using 3.5 kHz echo-sounding records and a piston core sample, Vicalvi *et al.* (1978) were able to establish that the shelf was exposed prior to the Late Glacial rise in sea level, and that the surface, which was mainly algal reefs and biodetritus, was deeply cut by fluvial drainage systems which drained into the adjacent continental slope. Early water-laid sedimentation within the depression was dated at 10620±300 BP using a subsurface mollusc shell from 66 m below

MLW. This sediment is largely continentally derived and analysis of foraminiferal and ostracod assemblages revealed a ß mesohaline to polyhaline salinity regime (10-24‰). The Depressão de Abrolhos had become a lagoon from *c.* 11000 BP, when the authors presumed a temporary still-stand at the present 60 m isobath (thus dating the -60 m scarp identified by Kowsmann *et al.* (1977). The rate of sedimentation was assumed to be 7 cm/1000 years within the lagoon, which lead to the conclusion that lagoonal sedimentation ended at *c.* 8200 years ago when sea water flooded the lagoon. This clearly must be highly speculative as it is impossible accurately to determine rates of sedimentation from a single date.

Kowsmann and Costa (1979), in a synthesis of the still-stand evidence from the Brazilian continental shelf, reviewed the data presented above and reported that morphological evidence had been found on the northern shelf for three additional still-stands. These erosion terraces correspond to the present 90 m, 75 m and 40 m isobaths and appear at similar depths to those reported by Corrêa *et al.* (1980) for Rio de Janeiro State (5.2.1).

5.2.4 The model-based approach

The empirical studies have all pointed to Holocene emergence of the Brazilian coastline, a phenomenon which Clark and Bloom (1979a) attempted to predict by modelling the response of the lithosphere to meltwater loading. The hydro-isostatic model was developed by Clark *et al.* (1978) and includes the gradual filling of ocean basins in response to northern hemisphere ice melt, deformation of the earth's solid surface and the geoid in response to the redistribution of mass and the redistribution of oceanic water so that the ocean surface lies on the geoid. It predicts emergence of between 2 to 4 m for continental South America since 5000 BP. The impact of Late Glacial melting of the Antarctic and Patagonian ice sheets was not considered by Clark and Bloom (1979a), but in an accompanying paper, incorporating the predictions of Clark and Lingle (1979) for Antarctica, Clark and Bloom (1979b) predicted that this would have had little effect upon sea level in Brazil post 5000 BP.

When Clark and Bloom (1979a) compared the predicted emergence for São Paulo and southern Rio de Janeiro State with the primary fossil index points of Suguio *et al.* (1980) there was relatively close agreement (the amount of predicted emergence being in error by less than 1.5 m). Mörner (1987), however, felt that the model predictions did not concur with levels of emergence recorded by Suguio *et al.* (1980) and Martin *et al.* (1985) and argued that there is no predictable and calculable relationship between sea-level rise and hydro-isostasy because of the complex interaction between changes in the geoid and mass distribution. Nevertheless, in the light of inconsistencies and of potential inaccuracies in the Brazilian sea-level index points referred to in 5.2.3, the nature and extent of anomolies remain to be established and as Nunn (1986) pointed out, it is the anomolies between model predictions and empirical evidence which can indicate the possible extent and magnitude of palaeogeoidal changes. Using a simple model Nunn showed that isostatic uplift and the passage of a positive geoid anomaly have a similar effect on coastal geomorphology. The Clark and Bloom (1979a) model will be considered further in 5.3.2.

5.3 Holocene sea-level changes along the Rio de Janeiro State Coast

The quality of local sea-level index points and their relationship with reference water levels will be assessed, then those deemed suitable will be used to produce a new time-altitude diagram for Rio de Janeiro State. A chronology of sea-level tendencies in Rio de Janeiro State during the Holocene will then be determined.

5.3.1 An assessment of local sea-level indicators

Sea-level index points published by Delibrias and Laborel (1971) and by Martin *et al.* (1979-80), and 16 index points indentified in the present study will be evaluated. These comprise peats, fine detrital muds and shells, particularly of worm gastropods and oysters. The indicative meaning of individual or grouped index points will be assessed, then the possible displacement of index points from their original altitude and the reliability of the age determinations will be considered.

5.3.1.1 Indicative meaning

For a feature to be regarded as a sea-level indicator it must have had a definite vertical relationship with tidal levels on the open coast or with a water level which is ultimately determined by such tidal levels. This vertical relationship is referred to as the indicative meaning and is expressed in terms of a reference water level such as local MHWS. In addition the vertical range over which the indicator occurs, or can occur, is referred to as its indicative range.

Peat formation may occur completely independently of sea-level change, so, in order to utilize a peat as a sea-level indicator it is necessary to verify that peat formation was in some way related to a tidal level. In the previous chapter such a relationship was established for peats of Holocene age at all sites except Itaipu-Açu Site 1, where the peat was determined to have formed independently of sea level. It remains, however, to establish the indicative meaning and range of these Holocene peats.

Although monocotyledonous fragments were recovered, the dated peats were consistently too highly humified to permit the identification of dominant peat forming species. These amorphous peats were classified as *Turfa* *herbacea* because of the presence of herbaceous roots, which indicated that they had formed *in situ*. The high degree of humification suggests that all the peats have been subaerially exposed, but their condition does not permit a more precise qualification because, as Janzen (1975) pointed out, inter-habitat variation in decomposition rates and species-specific decomposition rates within and between tropical habitats are almost totally undocumented. In mid-latitudes, such a high degree of humification would generally be considered to indicate a terrestrial rather than a telmatic origin, but the relatively high rates of decomposition in low latitudes and the presence of abundant diatoms through most of the peat strata that have been studied point to formation in a semi-aquatic environment.

Shennan (1980) noted that when two distinct deposits are found in sequence, without an hiatus, they must have formed in palaeoenvironments which existed side by side in space. Thus, assuming that the dated material is taken from such a boundary, as has happened in this study, the indicative range will correspond to the vertical range of the transition zone, rather than to the range over which the vegetation community responsible for peat formation occurs.

The stratigraphic evidence indicates that in all cases the onset of peat growth was associated with a relative fall in lagoon level which, bearing in mind the spatial relationship referred to above, points to peat formation at the lagoonal margin. The diurnal tidal variation in open lagoons and the seasonal water-level variation in closed lagoons (Figure 3.12) would provide the subaerial exposure necessary to produce a high degree of humification.

Indeed, humified freshwater peats are currently forming around the margin of the Maricá Lagoonal System where Gramineae, Cyperaceae and Typhaceae flourish between mean high lagoon level (MHLL) and mean low lagoon level (MLLL). The importance of the Typhaceae is indicated in several papers: Oliveira *et al.* (1955a,b), in a study of these lagoons, observed a zone of black, decomposing plant material at the waters edge where *Typha dominguensis* was dominant; Roncarati and Neves (1976) identified *T. dominguensis* as the dominant peat forming species in the Jacarepaguá Lagoonal System, which lies to the west of Baía de Guanabara; and Ferri (1980) stated that *T. dominguensis* is probably the most common Brazilian fen plant.

The brackish peats formed at the margin of open lagoons, a situation where both Roncarati and Neves (1976) and Zaninetti *et al.* (1977) distinguished between highly saline conditions, dominated by mangrove swamp, and less saline areas, dominated principally by *T. dominguensis.* The brackish peats of this study are not characteristic of mangrove deposition, where a high proportion of ligneous material and inorganic sediment would accumulate, so a community dominated by Typhaceae probably contributed most material to these peats. Alternatively, the dominant Brazilian saltmarsh taxon - *Spartina brasiliensis* - may have supplied the organic matter for these brackish peats.

Irrespective of the plant species responsible for peat formation, the evidence presented here indicates that they formed close to the lagoonal margin and this close association permits indicative meanings and ranges to be ascribed with some degree of confidence. A distinction can be drawn between peats associated with freshwater sediment - in which case they must be related to water levels in closed or virtually closed lagoons - and peats associated with brackish or marine sediment - in which case the evidence presented in the previous chapter indicates that they are related to tidal levels in open lagoons.

Table 5.4 Inferred indicative meanings and ranges for peat index points

Material	Indicative range (m)	Local reference water level	Altitude above MSL-Imbituba (m)
Freshwater peat directly above freshwater sediment	0.20	MLL	0.06 to 0.14[1]
Freshwater peat directly below freshwater sediment	0.20	(MLL + MLLL)/2	0.03 to 0.10[1]
Freshwater peat directly above brackish sediment	0.06	(HAT+ MHWS)/2	0.43
Freshwater peat directly below marine sediment	0.20	LHWN-20 cm	0.01
Brackish peat directly above brackish sediment	0.10	(MHW + LHWN)/2	0.26
Brackish peat directly below brackish/marine sediment	0.20	LHWN-20 cm	0.01

1. The smaller value relates to lagoons with small catchment areas and the larger to lagoons with large catchment areas

The peats associated with freshwater clastic sedimentation are assumed to have formed between MLLL and MHLL as this zone provides conditions suitable for the formation of highly humified peats in association with clastic sedimentation. The reference water levels (Table 5.4) reflect the nature of the association between the two depositional environments and the indicative range of 0.20 m corresponds to the mean difference between MHLL and MLLL in the five lagoons described in 3.4. Although van de Plassche (1977) pointed out that the indicative meaning of an index point is independent of its absolute height, a relationship can be established if suitable data are available, as here, where the lagoonal tide-gauge data have allowed the local reference levels to be related to MSL - Imbituba. Clearly, however, this relationship assumes that climatic conditions were similar at the time of deposition to those in 1980-82. A drier climate, with a less prominent wet season, for example, would produce a smaller indicative range and a lower reference water level with respect to MSL - Imbituba.

It is rather problematic to establish indicative meanings and ranges for peats associated with brackish and marine sedimentation, as there are no examples currently forming in the study area and the small amount of published data relating to the nature of such relationships in Brazil pertains mostly to mangroves. There are, nevertheless, a number of examples from mid latitudes which can be drawn upon. In the United Kingdom Fenland, Shennan (1980) related monocotyledonous peat above saltmarsh deposits to (MHWS + HAT) /2 -20 cm. As the tidal range in Rio de Janeiro is considerably narrower than that encountered in the Wash, it would be inappropriate to lower (MHWS + HAT)/2 by 20 cm, for this would reduce the reference level to MHT when in the Fenland it remains above MHWS. It would seem apposite to relate this transition zone in Rio de Janeiro to (MHWS + HAT)/2, as a similar salinity regime to that at the Fenland reference level is likely to be encountered. An indicative range of 6 cm (HAT-MHWS) is ascribed. In tidal areas of SW Netherlands, Glooper (1973) observed that in a brackish environment bare sand or mud is colonized by aquatic vegetation between 10 and 20 cm below local MHW, while Kaye and Barghoorn (1964), working in Massachusetts USA, stated that MHW is the critical level in determining the onset of saltmarsh deposition. The use of the latter tidal level in Brazil is supported by West (1977) who suggested that *Spartina brasiliensis* forms below MHW. Lowest high water neap (LHWN) - the level which is wet on every tide of the year - is taken to be the critical tidal level at which peat is overlaid by marine sediment. Hence the reference level for brackish monocotyledonous peat directly above brackish or marine sediment is taken to be (MHW + LHWN)/2 and the range to be 10 cm (MHW-LHWN). The reference level for the transition zone where peat is overlaid by marine sediment is assumed to be LHWN -20 cm with an indicative range of 20 cm. These reference levels are shown in Table 5.4.

As with local lagoonal reference levels, the local tidal levels (which are assumed to equate to tidal levels at Ilha Fiscal) have been related to MSL - Imbituba. This relationship could, however, have been influenced by palaeotidal changes and/or the floodbasin effect descibed by van de Plassche (1982). Davis (pers. comm.) assumed that any palaeotidal changes would be of small magnitude as the continental shelf and the present tidal range are both relatively narrow. The floodbasin effect may occur where coastal barriers with narrow inlets are associated with relatively large lagoons, allowing frictional forces to lower the reference water level with respect to the equivalent coastal water level. The diatom evidence is only consistent with the existence of a relatively narrow inlet when stratigraphic evidence points to there being a small water body behind the barrier, but the possibility of the floodbasin effect causing discrepancies between the Ilha

Fiscal tide gauge, in Baía de Guanabara, and tide levels on the open coast should not be ignored. Clearly, assuming that the tide gauges on the open coast, at Itaipú and Ponta Negra, have been levelled to the national datum, it would be preferable to utilize records from these sites, but attempts to obtain tidal data and to establish their relationships with MSL - Imbituba, through the Diretor de Hidrografia e Navegação, have proved fruitless. Nevertheless, comparison of a short tidal record from Ponta Negra (for January and February 1983) with predicted tide levels for Ilha Fiscal over the same period, suggests that it is valid to use the Ilha Fiscal tidal levels as local reference levels for the study area as a whole.

The fine detrital mud cannot be used as a water-level indicator because of the allochthonous nature of the deposit, coupled with the fact that it accumulated in an unknown depth of water. These samples will, however, be used in 5.3.3 in the determination of sea-level tendencies.

Indicative meanings and ranges can be established for *in situ* shells as indicated by van de Plassche (1977) who, for example, cited van Andel and Laborel's (1964) observation that living Vermetidae were to be found from 0.30 to 0.80 m above MLW on Cabo de São Agostinho, while in protected bays they were found to be approximately 0.30 to 0.60 m lower. However, the published shell index points have not been related to local tide levels but to the life zone of a living homologue or, if this was absent in the area of study, to the organisms which have replaced the former species in the present zonation. Thus differential heights are measured rather than absolute ones and these can be related to a chosen tide level - usually local MSL. The fossil shell is related to the top of the living zone and the vertical error margin is provided by the range of the living zone (or the fossil one if it can be measured). Laborel (1979) stated that:

"This method is quite a simple one and avoids the delicate problem of the evaluation of mean sea level, low tide level or any other purely hydrographical definition, which is a major difficulty when evaluating 'evaluated' sea levels of low altitude."

This approach is only really successful when the vertical range of the life zone is relatively restricted, as in the case of the Vermetidae *Petaloconchus (Macrophragma)* Carpenter which generally permits changes in level to be established to within ±0.5 m. *In situ Ostrea* shells occupy markedly wider life zones and may be found scattered at any height in the upper tidal zone. Laborel (1979) commented that there is a strong possibility of over estimating the height of the former sea level using fossil *Ostrea* shells, although the approach of Martin *et al.* (1979-80), in which the difference between the fossils and the top of the life zone is assumed to be a minimum elevation, appears to avoid this problem.

Allochthonous shells cannot be related to a tidal level nor to a living homologue, and as they do not indicate tendencies of sea-level movement they will not be considered further.

5.3.1.2 Altitudinal accuracy

While altitudinal lowering as a consequence of the consolidation of underlying sediments is generally not a problem with the published *in situ* shell data, as such shells were usually attached to a crystalline substratum, it is a very real problem for the peat samples collected in the present study. The shell samples influenced have however, been related to living homologues, so it is important to consider the possibility of differential displacement of living and fossil life zones and resultant altitudinal errors. In addition, although the occurrence of recent tectonic activity in the Guanabara Rift was considered and rejected in 5.2.3, and while the limited Vermetidae evidence suggests that there is no significant displacement between Cabo Frio and Baía da Ilha Grande as a consequence of such activity, the possibility of small amplitude tectonic displacements (of approximately 0.5 m) cannot be dismissed.

Consolidation is the process whereby a soft sediment is transformed into a rock, it involves recrystallization, dessication, cementation and above all compaction - the slow expulsion of pore water and the reduction of voids within a sediment as a result of overburden load. In some sediments, as Skempton (1970) pointed out with respect to clay, consolidation and compaction are almost synonymous terms and much of the following discussion will focus on compaction. This process has two distinct stages: primary compaction (the dissipation of excess macropores) and secondary compaction (the gradual readjustment of particles into a more stable configuration and/or the very slow drainage of water from micropores) (Berry and Poskitt, 1972).

Van de Plassche and Preuss (1978) stated that samples that have been lowered as a result of compaction can only be used to reconstruct former sea levels if the amount of lowering and the error interval can be reliably estimated or calculated.

> "*Yet, there is no field of knowledge where the problems of this assessment seem so difficult, almost intangible and beset by innumerable variable factors that will significantly influence conclusions drawn.*" (Greensmith and Tucker, 1986).

The overburden pressure imposed by the weight of the sediment column and the physical and chemical characteristics of the sediment are the principal factors determining the degree of compaction. As Greensmith and Tucker (1986) pointed out, deposition in most coastal regions over a period of more than a few thousand years is likely to be irregular, non-uniform and discontinuous with periods of erosion producing unloading and periods of deposition resulting in additional loading. The unloading could result in elastic rebound, though this was thought to be insignificant quantitatively in unconsolidated or poorly consolidated sediments. Discontinuities in sedimentation could result in periods when coastal deposits are subaerially exposed and subject to desiccation, leaching and cementation, all of which can alter the compaction characteristics of particular sediments. In addition, particle size characteristics and organic content of coastal sediments are highly variable, producing stratigraphic sequences in which individual strata respond differently to overburden pressures. Boswell (1961) suggested that peat strata may be reduced to 10%, clayey muds to 11-25% and sands to 66-75% of their original thickness which, in spite of these being maximum figures unlikely to be achieved in a Holocene coastal sequence, illustrates the potential complexity of the response of a sediment column to pressure. Berry and Poskitt (1972) stated that the compaction of peat is particularly complex because of its highly compressible nature and because the textures of peat are so variable.

In the study area the varied stratigraphic sequences, with frequent changes in constituent sediments, and the preponderance of highly compactable sediment underlying the peat strata make it difficult to assess accurately the amount of lowering that has occurred as a consequence of compaction. At Lagoa de Itaipú, for example, the oldest Holocene peat (*c.* 7-8000 BP) formed over a clay or clayey silt which in turn covers up to several metres of amorphous and occasionally fibrous peat. The sediments over which the Holocene peat lies are highly susceptible to compaction and, as Sandroni *et al.* (1984) determined, they have a high water content (110% for the clay and 200-450% for the peat) which suggests that the sediments are still undergoing primary compaction. Even so, the Itaipú peat is at a higher altitude than the comtemporaneous peat at Lagoa do Padre which lies over potentially less compactable clayey sand (5-11% clay content) and indurated clay.

In order to resolve such anomalies and to model accurately the response of the different sediment types to compaction it is essential to obtain age and altitude data for sea-level indicators which have been unaffected by compaction. An example would be to sample and date the bottom of a Basis Peat (basal peat which has formed in a more or less constant relationship to sea level, van de Plassche, 1977) lying over uncompactable material, an approach utilized successfully by Bloom (1964) on a Connecticut coastal marsh. There is, however, a dearth of suitable Basis Peats or other sea-level indicators unaffected by compaction in the study area.

Younger peat strata (*c.* 2300 to 2700 BP) at Lagoa de Padre and Itaipu-Açu also display considerable altitudinal variation between samples of similar age. Comparison with Vermetidae samples from Baía da Ilha Grande and Cabo Frio suggests that there is probably less lowering due to compaction at Lagoa do Padre than at Itaipu-Açu, where the peat may have been displaced by about 1.0 m, yet there is a greater thickness of potentially highly compactable material at Lagoa do Padre.

It has not been possible to estimate reliably, or to calculate the amount of lowering which has occurred to peat index points due to consolidation (essentially compaction), so altitudes derived from such strata can only be used as altitudinal minima. This is the principal weakness of the adopted methodology of sea level research when compared with the fossil based approach of van Andel and Laborel (1964).

As far as *in situ* fossil shells are concerned, Laborel (1986) warned that where Vermetidae remains are more or less fragmented, as in Brazil, it is better to be pessimistic about the level of precision which can be achieved, especially if modern Vermetidae are absent from the present zonation as they are in Brazil south of Cabo Frio. Laborel also expressed concern that some of the São Paulo Vermetidae are half covered by sand beaches which could not have been present when the animals were alive. Such spits may have important consequences on the local tidal range inside the bay causing vertical displacement of the biological zones. Possible changes in wind patterns and intensities during the Holocene could also cause displacements of the biological zones of both Vermetidae and *Ostrea*. Laborel commented that:

> *"Such variations could give birth to 'elevated' vermetid lines and I feel now that such a phenomenon may have been completely overlooked by myself and other authors, notably on the Brazilian coast."*

5.3.1.3 Accuracy of age determinations

A number of factors may affect the the accuracy of ^{14}C age determination on peat and detrital mud samples. The infiltration of water containing organic carbon in solution or colloidal form could rejuvenate older peats, and such fulvic and humic acids were not removed by chemical pretreatment in Kiel because of the highly humified nature of many of the peats. The highly compactable nature of the organic deposits discussed in 5.3.1.2, combined with the need to take thick samples for dating, means that samples at the base of a peat or mud layer are likely to be rejuvenated while those at the top of the stratum are likely to be too old - thus reducing the age differential between the top and bottom of any dated stratum. The deposition of older allochthonous organic matter within the fabric of a peat or mud as it forms would produce dates which are too old; herbaceous detritus of this type is difficult to detect, but any woody detritus was removed before the samples were submitted for dating. The rejuvenating effect of root contamination has also been reduced by removing roots and rootlets, as described in 2.5. Mook and van de Plassche (1986) stated that material of different ages may be mixed by soil organisms and that dark amorphous peat is likely to have been subject to such soil organism activity. As the peats used here contain distinguishable plant remains they are, despite their high degree of humification, considered suitable for dating.

Mook and van de Plassche (1986) identified several factors which may affect the accuracy of ^{14}C age determinations on shells. Inaccuracy can arise from differences in standard laboratory practice; marine shells yield $\delta^{13}C$ values of about 0‰ requiring a fractionation correction of + 400 years, but this is equal and opposite to the apparent age correction which is necessary to compensate for the reservoir effect. This latter effect arises because the upwelling of deep oceanic water containing less ^{14}C reduces the ^{14}C activity of dissolved carbon in surface waters (upper 100 m) by about 5%, equivalent to 400 years. Some laboratories apply only the fractionation correction, so that the reported ages are 400 year too old. Neither correction is mentioned by Delibrias and Laborel (1971) or Martin *et al.* (1979-80). In addition, the ^{14}C content of *in situ* shells may be disturbed by the infiltration of sea or ground water and the formation of secondary carbonate on or in the shell (by the evaporation of water or by loss of CO_2). This secondary carbonate can be recognized by differences in colour or structure, but it may not have been considered when the shell samples were submitted for dating.

As three laboratories (Kiel, Gif-sur-Yvette and Bahia) have furnished dates an additional source of bias may have been introduced. The work of the

International Study Group (1982), in which 20 different ^{14}C laboratories were each asked to date independently eight replicate samples from a single tree, revealed the existence of unexplained inter-laboratory variability and systematic bias. The results were, however, in general agreement.

5.3.2 A time-altitude diagram for Rio de Janeiro State

The index points which were considered, in 5.3.1, to be suitable time-altitude indicators have been plotted on an age-altitude diagram (Figure 5.8). These comprise *in situ* Vermetidae limestone samples (the most altitudinally reliable), *in situ Ostrea* shell samples (accurate altitudinal minima) and *Turfa herbacea* samples (the least altitudinally accurate due to the effect of consolidation).

The Vermetidae index points, taken from the work of Delibrias and Laborel (1971) and Martin *et al.* (1979-80), have been related to MSL-Ilha Fiscal. As mentioned in 5.2.2, Delibrias and Laborel (1971) described sample L11 as being 3.0 m above its present day homologue, yet Delibrias *et al.* (1971) stated that it was 2.6 m above this level. The 3.0 m differential, which has been cited in subsequent publications by other authors, is used, but the smaller differential is also indicated on Figure 5.8 with a dashed error box. Martin *et al.* (1979-80) ascribed ± 0.4 m error to the Vermetidae altitudes, but following the recommendation of Laborel (1986), these have been amended to the more pessimistic ± 0.5 m error range, quoted by Delibrias and Laborel (1971). In the case of sample A321 for which two different dates have been published (2695 ± 130 BP and 2450 ± 130 BP), the older age, cited in all but one publication, is used.

The *in situ Ostrea* samples of Martin *et al.* (1979-80) are plotted as altitudinal minima in relation to MSL-Ilha Fiscal. The *O. arborea* Chemnitz samples of

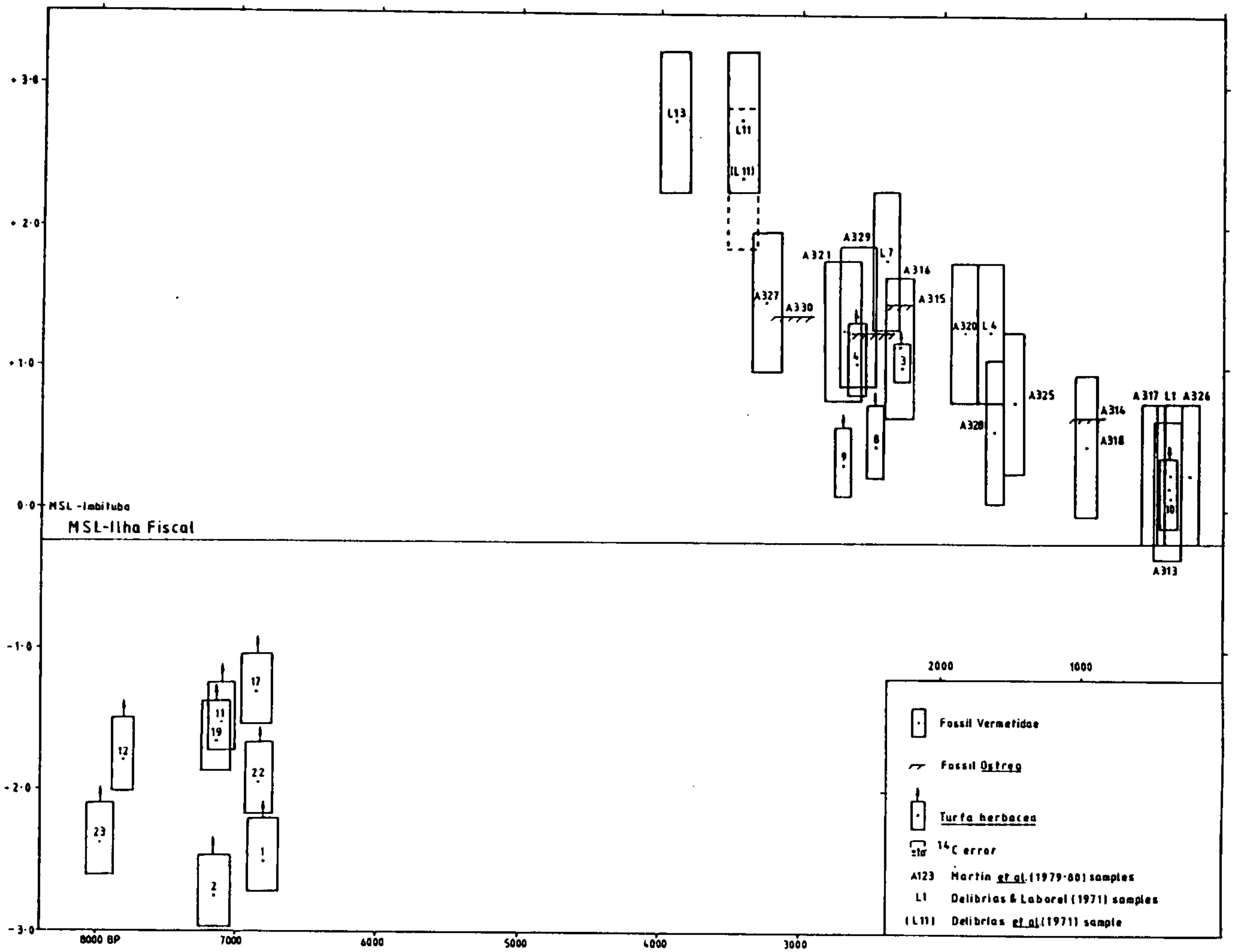


Figure 5.8 An age-altitude diagram for Rio de Janeiro State

Curray and Danciger, taken from 4.8 m above MSL, are almost certainly allochtonous and are not plotted on Figure 5.8.

The altitudinal position of *T. herbacea* samples, collected by the author, have been amended according to the appropriate indicative meaning (Table 5.4). The vertical error margin of each sample reflects the stratigraphic sampling error (Table 2.1), the closing error which resulted during levelling (Table 2.3) and the indicative range (Table 5.4). An arrow at the top of each error box indicated that the altitudinal position has almost certainly been lowered by the process of consolidation (5.3.1.2). *T. herbacea* sample 20 was rejected because it is believed to be contaminated by older carbon (see discussion in 4.6.3).

Figure 5.8 illustrates that relative MSL was approximately 1 m below MSL-Ilha Fiscal at *c.* 7000 BP, then at *c.* 4000 BP it was approximately 3 m above MSL from whence it fell to present MSL-Ilha Fiscal, but it does not indicate what levels were attained during the intervening 3000 year period. Evidence from Lagoa do Padre helps to fill this gap in the time-altitude record. This evidence, presented in 4.3.2, indicates that during the period between *c.* 6000 BP and 5230 ± 90 BP, when Site 2 was open to the ocean, the maximum elevation of HAT (as represented by the sand stratum at LP-2/4) was 2.29 m above MSL-Imbituba (Figure 4.9) which is equivalent to a mean level of + 1.83 m (MSL-Ilha Fiscal). Then in the period between 4850±80BP and 2690±65 BP, when the 5230 BP barrier was overtopped, the maximum Holocene sea-level elevation must have been achieved. The waterlaid sediment on the barrier across the mouth of the inlet indicates a maximum elevation for HAT of 3.5 m above MSL-Imbituba, which equates to a mean level of + 3.0 m (MSL-Ilha Fiscal). To the seaward, the barrier across the eastern part of Lagoa do Padre is believed to have sheltered the site from the impact of storm waves.

The LP-2/4 sand stratum was probably not lowered significantly due to compaction, as the underlying clay was indurated, but the possibilty of post-depositional lowering cannot be ruled out. The detailed stratigraphy at the high point of the barrier was not sampled, but the stratigraphy of LP-2/3 (Figure 4.9) points to it being predominantly sand and thus altitudinally reliable.

A MSL of 3.04 m above MSL-Ilha Fiscal between 4850 and 2590 BP is consistent with Vermetidae sample L13, shown in Figure 5.8, and with the maximum altitude of +2.55 to +3.05 m for beach sediment and of +2.70 m for *Echinometra* burrows, recorded by Cunha and Andrade (1977) in Baía de Guanabara. This points to a maximum Holocene MSL elevation of + 3.0 m at *c.* 4000 BP. The evidence presented above suggests that at *c.* 5100 BP, when Martin *et al.* (1985) identified maximum Holocene sea-level elevations along much of the Brazilian coast (largely based upon terrace-level evidence), MSL in Rio de Janeiro State was little higher than + 1.8 m and not at + 4.8 m.

The spherical earth model of Clark and Bloom (1979a) predicted a maximum Holocene MSL of +3 m in Baía da Ilha Grande, which is consistent with the field evidence presented here, but rather than attaining this altitude at *c.* 4000 BP, it was achieved at *c.* 5000 BP. Also the model predicted that MSL would have been approximately 4 m below the present level at *c.* 7000 BP, which is too low by approximately 3 m when compared with the field evidence.

The age discrepancy of *c.* 1000 years could be attributed to inaccurate age determinations, although there is a small probability that five samples, comprising three different materials would have been rejuvenated in a more or less consistent manner. Thus, while the field data could be in error, it is more likely that the model assumptions were inadequate. The assumption of no eustatic change since 5000 BP may, for example, require modification. The altitudes recorded in the field for *c.* 7000 BP surfaces may have been lowered by compaction, but they have almost certainly not been elevated, so the model is presumed to be in error at this time.

5.3.3 Determination of sea-level tendencies for Rio de Janeiro State

The exploratory approach to the analysis and interpretation of Holocene sea-level data, proposed by Shennan *et al.* (1983) and effectively employed in the United Kingdom, will be applied to the lagoonal data (both *Turfa herbacea* and *Limus detritus* samples) and to the Vermetidae samples from Baía da Ilha Grande and Cabo Frio.

As Shennan *et al.* (1983) stated:

> *"Detailed interpretation of regional phenomena cannot be made from an evaluation only of sea-level index points on a time-altitude diagram, because the errors involved in the estimation of past altitudes permit only the identification of broad sea-level band ..... Correlation schemes based on the sea-level tendency concept offer an alternative approach."*

While the precise response of sedimentary systems, and Vermitidae or *Ostrea* populations to sea-level change will be local and site dependent, the dominant direction of sea-level change will be constant and should be recorded over a much wider area. This wider expression of sea-level change is referred to as a tendency of sea-level movement (Shennan *et al.*, 1983).

In Figure 5.9c the distribution of 15 radiocarbon dates from Lagoa do Padre, Itaipu-Açu and Lagoa de Itaipú is shown in combination and the interpretation of their relationship to a positive or negative tendency of sea-level movement is given. The stratigraphical and micropalaentological

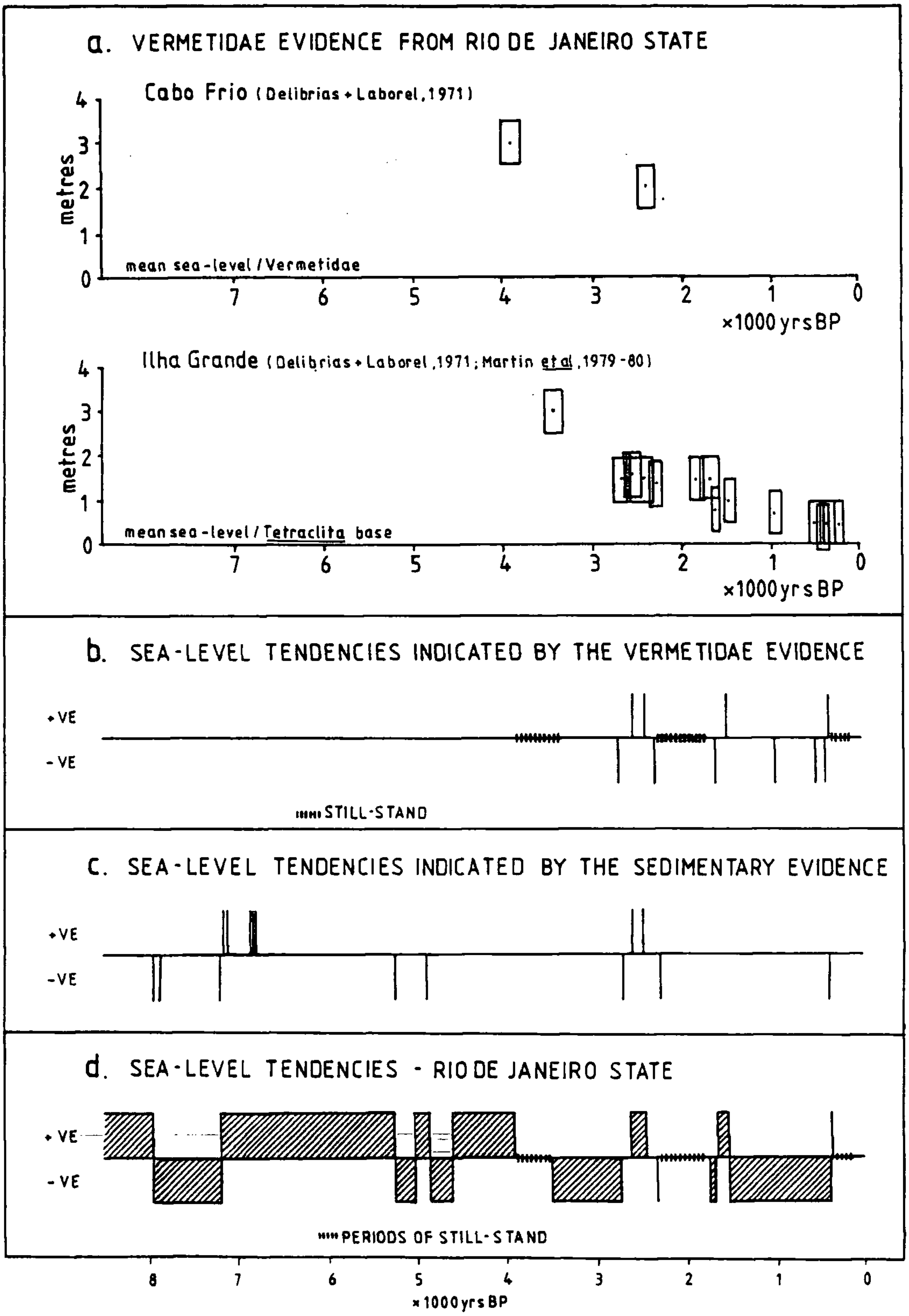


Figure 5.9 A partial chronology of sea-level tendencies in Rio de Janeiro State

evidence presented in Chapter 4 permitted eight dated transgressive overlaps and seven dated regressive overlaps to be interpreted, respectively, as eight positive and eight negative tendencies of sea-level movement. The chronology proposed by Ireland (1987) has been modified as re-evaluation of the field evidence indicated that the 4850 ± 80 date from LP-2/12, which was taken to mark a positive tendency, marks the beginning of a regressive overlap and a negative tendency.

Undated bio- and lithostratigraphic evidence permitted the identification of additional overlaps at all sites indicating that certain events, which are only dated at a single site, have a wider expression : at Lagoa do Padre (4.3.3) a total of five transgressive and five regressive overlaps were identified between *c.* 8200 BP and *c.* 2000 BP; at least four transgressive and four regressive overlaps were identified at Itaipu-Açu over the same period (4.5.3); and there was clear indication of four transgressive and four regressive overlaps, between *c.* 8200 BP and the present at Lagoa de Itaipú (4.6.3).

Tendencies of sea-level movement can also be inferred from the Vermetidae data from Cabo Frio and Baía da Ilha Grande (Figure 5.9a and b) although tendencies derived solely from comparison of Vermetidae altitudes must be tentative, as they are subject to altitudinal uncertainty. The age and altitude of adjacent Vermetidae samples are considered, sequentially from oldest to youngest: if the adjacent sample is at a lower altitude a negative tendency is indicated, if at a higher altitude a positive tendency is indicated, and if at the same altitude a still-stand is indicated. Where sedimentary and Vermetidae evidence coincide temporally, the same sea-level tendencies are indicated, so the Vermetidae evidence reinforces the sedimentary evidence. The still-stands identified from the Vermetidae evidence may represent periods of weak positive or negative tendency which are marked by inherent dating and altitudinal measurement problems. The existence of true periods of still-stand requires verification, but, at present, the Vermetidae evidence provides the most altitudinally sensitive index points and it is unlikely that sedimentary sequences will provide the same quality of altitudinal resolution.

When the tendencies identified in Figure 5.9b and c are considered in conjunction with the stratigraphical and diatom analytical evidence, a partial chronology of tendencies of sea-level movement can be inferred. Figure 5.9d indicates that the period between *c*. 7000 BP and *c*. 4000 BP was dominated by positive sea-level tendency and that the period between *c*. 4000 BP and the present was dominated by negative tendency. This is consistent with the theoretical and empirical evidence which shows that the Brazilian coast is emergent. The theoretical evidence is provided by the spherical earth model prediction of Clark and Bloom (1979a), while the empirical evidence is provided by the available Vermetidae evidence from different coastal areas of Brazil and by the lagoonal evidence from the coast of Rio de Janeiro State. Figure 5.9d also shows, however, that during both periods the dominant tendency was interrupted by shorter periods during which the opposite tendency prevailed. Thus, while it is possible to trace a smooth sea-level curve through the error boxes shown in Figure 5.8, the evidence presented here suggests that it would be inappropriate to do so, as minor sea-level fluctuations are superimposed upon the general trends.

5.4 Barrier development in the study area

In this section the chronology of barrier formation will be considered, then modes of barrier migration will be discussed.

5.4.1 A chronology of barrier development

Muehe (1982) produced his chronology of barrier formation (Table 5.1) by correlating the maximum height of waterlaid sediment on each barrier with the sea-level curves of Suguio and Martin (1981). Evidence presented in Chapter 4 indicates that the age ascribed by Muehe to several of the barriers was in error and that most barriers had a relatively complex history, so that attributing a single date to their formations was misleading. Subsequently, in 5.3.2, the sea-level curve upon which the chronology was based was shown to be inaccurate, most significantly the +4.8 m MSL maximum at *c.* 5100 BP, which Muehe used to date the fossil barriers at Lagoa de Itaipú, Itacoatiara and Itaipu-Açu was shown to be approximately 3 m too high. In addition, two inconsistencies in the chronology were noted in 5.2.1. There is consequently a need to produce a revised chronology of barrier development for the study area.

Muehe (1982) considered all the barriers to be of Holocene age, but in 4.5.3 and 4.6.3 hypotheses were presented which required the fossil barriers at Itaipu-Açu and Lagoa de Itaipú to have formed during the 'Last' Interglacial. Additional evidence will now be presented which supports a 'Last' Interglacial origin not only for these barriers, but for the fossil barriers at Itacoatiara, Lagoa de Maricá and Lagoa do Padre.

Table 5.5 shows the maximum altitudes of waterlaid sand on present and fossil barriers for the lagoons considered by Muehe (1982) and for Lagoa do Padre as recorded by the author. These show a relatively consistent picture with a mean altitude of 10.6 m for the fossil barriers and 6.6 m for the present-day barriers. This mean altitude of 10.6 m for the fossil barriers is clearly inconsistent with a maximum Holocene MSL of +3 m at *c.* 4000 BP.

The evidence presented in Chapter 4 indicates that the Lagoa de Itaipú and Lagoa do Padre sites were relatively protected from the onset of Holocene

Table 5.5 Altitudes of present day and fossil barriers in the study area

Lagoon	Present barrier altitude (m)	Fossil barrier altitude (m)
Piratininga	6.0	-
Itaipú	7.0?	10.0-12.0?
Itacoatiara	7.0?	11.0?
Itaipu-Açu	7.4	12.2
Maricá	7.0	9.0
Guaratiba	6.0	-
Padre	6.0	10.0
Guarapina	6.0	-

sedimentation, which is consistent with the presence of fossil 'Last' Interglacial barriers at both sites. Indeed, at Lagoa de Itaipú, as mentioned in 4.6.3, the archaeological evidence from the Sambaqui de Camboinhas (Kneip *et.al.*, 1981), indicates that preceramic indians were living on the fossil barrier approximately 7 m above present MSL - Ilha Fiscal at 7958 ± 224 BP, when the evidence indicates that MSL was approximately 2 m below MSL - Ilha Fiscal (Figure 5.8). The sea level at this time could not possibly have produced such an elevated barrier.

Biological evidence also supports the hypothesis that the fossil barriers are of considerable age. The *restinga* vegetation is extremely sparse on the recent barriers, yet is very rich in both species and form on the fossil barriers, suggesting that it has had markedly more time in which to develop. Along a 93 m transect from the beach to the lagoon of Guaratiba (where there is only a single present-day barrier) 76% of the ground is unvegetated and only 12 species were recorded. With the exception of an 83 cm tall bush of *Sophora tomentosa,* all were ground hugging herbs. A 450 m transect across both present-day and fossil barriers at Lagoa do Padre revealed a similar picture for the present-barrier transect, where 83% of the ground was unvegetated and where 26 species (including 11 of those found at Guaratiba) were recorded. The tallest of these was the grass *Spartina ciliata* which reached a height of 50 cm. In contrast, only 43% of the fossil-barrier transect was unvegetated, 70 species were recorded (of which 14 were also found on the present-day barrier) and the tallest species was *Clusia fluminensis* at 730 cm. Interestingly, Rodicka (1980), in a study of the *restinga* vegetation of Pontal da Barra, Maceió (Alagoas State), recorded 27 species (8 of which were recorded on the present-day barriers in the study area), which suggests that the numbers of species recorded on the present-day barriers of the study area are not atypical. The pattern of a more species-rich vegetation on the fossil barriers is repeated throughout the study area.

A period of isolation of thousands of years, which would have followed the marked fall in sea level during the 'Last' Glacial is supported by the presence of a small, sand-coloured lizard, *Liolemus lutzae*, which lives in trunks and under dead wood (a habitat not encountered on the present-day barriers) and which is, according to Dansereau (1947), endemic to the littoral of Rio de Janeiro. This type of speciation is not consistent with the potential for free migration which is likely to have prevailed along the mid-glacial shoreline.

The detailed histories of the Holocene barriers of Lagoa do Padre, Lagoa de Guaratiba, Itaipu-Açu and Lagoa de Itaipú were presented towards the close of 4.3.3, 4.4.3, 4.5.3 and 4.6.3 respectively. In broad terms these indicated that the Holocene barriers formed at *c.* 7200 BP. Those at Lagoa do Padre and Lagoa de Guaratiba were later breached and barriers formed across many embayments to the landward of the present-day lagoons. Subsequently, the present barriers formed at *c.* 2300 BP. The barriers at Lagoa de Itaipú and Itaipu-Açu were not subsequently breached, but an inlet persisted until relatively recently at Lagoa de Itaipú. The present altitudes of these latter barriers would have been determined at *c.* 4000 BP during the phase of maximum Holocene sea-level elevation, and the lower altitudes of the Lagoa do Padre and Lagoa de Guaratiba barriers reflect the fact that they formed approximately 1700 years after this maximum Holocene sea level. It is tentatively proposed that other barriers at 6.0 m altitude (Table 5.5) were breached during the Holocene and also formed at *c*. 2300 BP.

5.4.2 Barrier migration in Rio de Janeiro State

There are two principal schools of thought pertaining to barrier migration in response to sea-level rise: in the first hypothesis, which can be traced back to Gilbert (1885, 1890), barrier over-stepping and stepwise retreat of the surf zone landward is postulated; while in the second, which can be traced back to Johnson (1919), barriers are said to migrate continuously by shoreface retreat.

The migration of Long Island, New York has been the subject of recent debate. Rampino and Sanders (1980, 1982, 1983) favoured discontinuous retreat by inplace drowning of barriers, as well as continuous migration, the former occurring during phases of rapid sea-level rise; while Swift and Moslow (1982), and Leatherman (1983a) argued that continuous migration, which may be intermittent in time, is the only process required to explain the evidence. In Rio de Janeiro State there is evidence to support the synchronous occurrence of both continuous migration and of over-stepping in different parts of the same coastal area. The former is believed to have occurred at Itaipu-Açu and the latter at Lagoa do Padre.

At Itaipu-Açu, Muehe and Ignarra (1984) concluded that the beach rock which lies approximately 80 m offshore (Figure 5.1) formed at the base of the present barrier during a regressive phase at *c*. 2800 BP, and that the barrier subsequently migrated landward at a rate of 3 cm/year. The field evidence presented in Chapter 4 suggests that the beach rock is likely to be considerably older, having formed during a regressive phase shortly after the barrier formed at *c*. 7200 BP. This would point to an average rate of landward migration of only 1 cm/year. Irrespective of the rate of migration, however, the diatom evidence (Figure 4.24) indicates that this barrier was never overstepped, so it must have migrated by shoreface retreat. The series of positive and negative tendencies recorded at Itaipu-Açu suggest that this landward migration would have been discontinuous in time.

In contrast, at Lagoa do Padre the closed barrier which formed at *c*. 7200 BP, producing oligohaline water conditions in the lagoon, was later over-stepped. Marine water replaced oligohaline and the surf zone stepped into the inlets which lie to the landward of the present lagoon. New barriers then formed across these inlets at *c*. 5200 BP.

It is not clear why the two systems responded differently, but it is possible that where a fossil barrier backed the new barrier, its presence prevented over-stepping and the barriers simply came together or actually merged as at Lagoa de Itaipú and Itacoatiara. It is also likely that there were differences in the sediment supply along the coast - a factor which many authors (including Dillon, 1970; Kraft *et al.*, 1979; Leatherman, 1983b; and Rampino and Sanders, 1980) consider to be a principal factor determining barrier migration.

While the precise mode of barrier migration along the continental shelf cannot be established from the evidence collected to date (described in 5.2.1 and 5.2.3), the work of Corrêa *et al.* (1980) in Rio de Janeiro State suggests that the migration was intermittent in time.

5.5 Inter-regional correlation of sea-level tendencies

In this section an attempt will be made to compare the sea-level tendencies

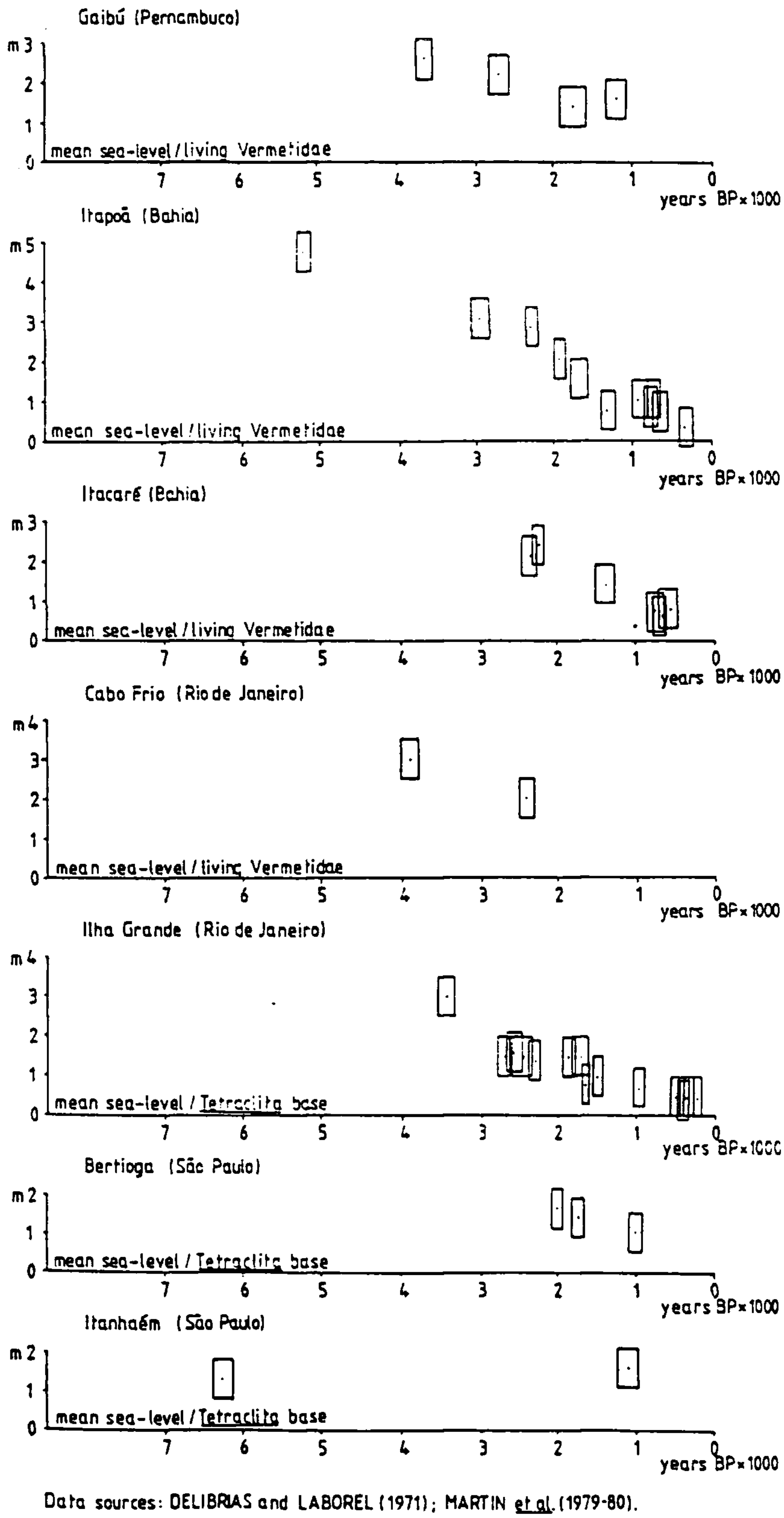


Figure 5.10 Graphs showing the elevation and age of ^{14}C dated Vermetidae samples from Brazil

identified in Rio de Janeiro State (Figure 5.9d) with tendencies inferred from published data which relates to other parts of Brazil. In other regions only one type of published index point - Vermetidae limestone can be used with any degree of confidence to derive detailed sea-level tendencies, as all other published index points (discussed in 5.2) are subject to unacceptably large altitudinal uncertainties. Nevertheless, as pointed out in 5.3.3, Vermetidae index points are also subject to altitudinal uncertainties and tendencies inferred by comparing altitudes of fossils of different age will not be as reliable as those determmined by careful analysis of coastal sedimentary sequences. In addition, only Vermetidae limestone which formed after 4000 BP has generally been preserved, so no comparison is possible with the pre-4000 BP Rio de Janeiro State record.

On a time scale of several thousand years, the Vermetidae evidence (Figure 5.10) indicates a general regressive tendency in all regions after 4000 BP, which is consistent with the emergent nature of the Brazilian coastline. It is, however, the relatively short periods (several hundred years) of positive sea-level tendency and still-stand which must be inter-regionally correlated if these tendencies are to assume more than a local significance. All positive tendencies indicated by the Vermetidae evidence outside Rio de Janeiro State are detailed in Table 5.6, which reveals only a maximum of two positive tendencies in any region. No still-stands are indicated. The positive tendencies would appear not to be regionally significant as only the oldest Itapoã phase, the Gaibú phase and the 1630 to 1490 BP Rio de Janeiro phase exhibit slight temporal overlap.

Such weak correlation may, however, be a reflection of the fragmentary nature of the Brazilian Vermetidae fossil record. The absence of fossils indicating positive tendencies of sea-level movement does not necessarily imply that there were no such tendencies. There is a clear need for detailed

Table 5.6 Periods of positive tendency of sea-level movement inferred fromVermetidae evidence

Coastal region	Periods of positive tendency post 4000 BP(years BP)
Gaibú	1750 to 1190
Itapoã	1360 to 950 and 830 to 770
Itacaré	2335 to 2250 and 680 to 575

analysis of coastal sedimentary sequences outside Rio de Janeiro State, utilizing the techniques employed in this study, in order to facilitate inter-regional comparison of detailed sea-level tendencies.

6. CONCLUSIONS

The sedimentary history of the lagoons and barriers in the study area will be summarized, the evidence for, and the nature of, Holocene sea-level changes in Rio de Janeiro State will be outlined, the applicability of the adopted research methodology will be discussed, and finally possible future research work will be considered.

6.1 The sedimentary history of the lagoons and barriers of the study area

The sedimentary history of the lagoons and barriers of the study area has been shown to be markedly more complicated than was previously envisaged (Muehe, 1982). All the barriers (or *restingas*) were believed to have enclosed lagoons in which considerable quantities of sediment had accumulated during the Holocene, for example 9 m of fine sediment was assumed to have accumulated in Lagoa de Itaipú since 5100 BP, and both fossil and present-day barriers were thought to be of Holocene age.

Evidence presented in Chapters 4 and 5, which includes the results of sedimentary and diatom analyses and 25 new radiocarbon age determinations, indicates that much of the unconsolidated sediment in the study area is in fact pre-Holocene with, for example, only 2 m having accumulated in Lagoa de Itaipú since 7000 BP. This rate of accumulation of approximately 3 cm per 100 years seems typical of all the lagoons studied.

The lagoons at the sites studied have had a varied history. Lagoa de Itaipú remained open until relatively recently, but the size of the inlet and extent of marine influence has gradually declined. At Itaipu-Açu a fresh to oligohaline lagoon formed between the present and fossil barriers probably around 7200 BP, but it eventually disappeared some time after 2460 BP in response to barrier migration, relative fall in sea level and sediment accumulation. It is evident that there was never a lagoon behind the Itaipu-Açu fossil barrier at least in the west of the Itaipu-Açu coastal plain. At *c.* 7200 BP Lagoa do Padre and almost certainly Lagoa de Guaratiba became oligohaline water bodies protected from the ocean by a barrier. Subsequently they became relatively open bays in which marine conditions prevailed for several thousand years before the formation of the present-day barriers and the return of oligohaline water.

Fossil barriers, which are present at Lagoa de Itaipú, Itacoatiara, Itaipu-Açu, Lagoa de Maricá and the eastern end of Lagoa do Padre and were believed to date from 5100 to 3700 BP, are now believed to have a 'Last' Interglacial origin. This conclusion is supported by the average fossil barrier altitude of 10.6 m, which is incompatable with their formation during the period of maximum Holocene sea-level elevation, by sedimentary and archaeological evidence which indicates that the barriers were present very early in the Holocene, and by biological evidence which points to the fossil barriers being considerably older than the present-day barriers.

Two distinct patterns of Holocene barrier evolution have emerged. Those at Lagoa de Itaipú, Itaipu-Açu, and probably Itacoatiara and Lagoa de Maricá are believed to have formed to the seaward of the present barriers at *c.* 7200 BP and have subsequently migrated landward by shoreface retreat until they lie adjacent to, or have merged with, the existing 'Last' Interglacial barriers. In contrast, the evidence suggests that those at Lagoa do Padre (which was only partially protected by a fossil barrier), Lagoa de Guaratiba, and probably Lagoa de Piratininga and Lagoa de Guarapina, formed at *c.* 7200 BP, but were later over-stepped as the surf zone jumped to the landward extreme of the present-day lagoons. Barriers formed across many small bays which lie around these lagoons, probably at *c.* 5200 BP, then later, following a regressive phase, the present barriers formed at *c.* 2300 BP.

This evidence indicates that the fossil barriers and those present-day barriers backed by, or merged with, fossil barriers are relatively stable and, as such, are the most suitable for the type of housing development which is proceeding along this coastline. Ironically, however, this development is likely to destroy much of the *restinga* vegetation which has probably played an important role in stabilizing the fossil barriers.

6.2 Sea-level change in Rio de Janeiro State

A new time-altitude diagram for Rio de Janeiro State has been produced using both new and existing evidence. From a total of 26 index points published by other workers, 20 *in situ* Vermetidae and *Ostrea* samples were judged to be altitudinally reliable. In addition 13 new *Turfa herbacea* index points were used, although problems of assessing the impact of compaction mean that they are the least altitudinally reliable. Supporting evidence was provided from undated sedimentary sequences and fossil *Echinometra* burrows.

Tendencies of sea-level movement have been inferred using *T. herbacea* and *Limus detritus* samples, supported by diatom and sedimentary evidence, and from Vermetidae index points. The latter are considered to be less reliable, but when sedimentary and Vermetidae evidence coincide termporally the same sea-level tendencies are indicated.

At Lagoa de Itaipú evidence has been presented (4.6.3) which may indicate a high interstadial sea level at *c.* 35000 BP. While this is consistent with the findings of Thom (1973) and Kowsmann and Costa (1979), the evidence is not incontrovertible and climatic oscillation between relatively wet and relatively dry periods would provide an alternative explanation.

The time-altitude diagram (Figure 5.8) and supporting evidence, particularly from Lagoa do Padre Site 2, indicate that relative MSL rose from approximately -1.0 m (Ilha Fiscal) at *c.* 7000 BP, to about +1.8 m at *c.* 5200 BP and to +3.0 m at *c.* 4000 BP, then gradually fell to its present level. This is at odds with the published curve of Martin *et al.* (1979-80) for southern Rio de Janeiro State (Figure 5.4e) which indicates that there was a maximum MSL of +4.8 m at 5200 BP and a sea-level low at *c.* 4000 BP. It has been argued, however, that the *Ostrea arborea* Chemnitz shells which provide the evidence for the 5200 BP maximum are allochthonous and that there is no evidence for a 4000 BP sea-level low.

Using the sea-level tendency approach of Shennan *et al.* (1983), potential sea-level fluctuations of short duration (a few hundred years or less) have been recognized (Figure 5.9d). Two negative tendencies around *c.* 5000 BP, when the general tendency is positive, and three positive tendencies between 3000 BP and the present, when the general tendency is negative, have been identified. It has not been possible to establish the regional significance of these short duration tendencies, with post 4000 BP Vermetidae evidence suggesting that there is little inter-regional correlation. However, until data of similar quality are collected in other states the regional significance of such variations cannot be reliably assessed.

The field evidence presented in this study is consistent with the maximum Holocene emergence predicted by Clark and Bloom (1979a), using their spherical earth model, but it deviates from the model's predictions in two significant respects. Firstly, the maximum altitude is reached 1000 years later than Clark and Bloom (1979a) predicted, suggesting that the model assumption of no eustatic sea-level change since 5000 BP may require amendment. Secondly, the predicted altitude for 7000 BP is 3 m too low. These discrepancies suggest that the predicted rate of sea-level rise prior to 7000 BP was too slow and that the predicted rate was too rapid post 7000 BP.

Martin *et al.* (1985) related altitudinal descrepancies between different coastal regions at *c.* 5100 BP, to the migration of the geoid surface in a WSW to ENE direction, but this migration only produces altitudes which are relatively consistent with their field evidence between the States of Paraná and Rio de Janeiro. In Santa Catarina it would produce 1.0 m too little emergence and an altitudinal anomaly of 0.5 m would result between Ilheus and Salvador in Bahia State. Most of the 5100 BP altitudes are, however, based upon terrace altitudes which have been indirectly dated using *sambaqui* shells (hence only age minima). Indeed, Fairbridge (1976) stated that all these terraces were pre-Holocene. It was not possible to consider the altitudinal accuracy of all terraces, but the interpretation of a +3.5 to 4.0 m sea-level high at Cananéia, based upon the elevation of a wave-cut terrace of limited spatial extent, was shown to be unreliable. In addition, the + 4.8 m maximum in Rio de Janeiro State, based on the Curray and Danciger shells has been shown to be approximately 3 m too high.

6.3 The methodology

The methodology, which evolved in the study of temperate coastlines with a meso- or macrotidal range, has proved equally applicable to a microtidal, tropical coast. Indeed, the diatom analytical technique, as developed in this study, was essential in allowing the relationship between tidal levels on the open coast and sedimentary sequences in and around the lagoons to be established through time.

Such micropalaeontological techniques set this methodology apart from those relying only on the description and dating of sedimentary sequences, but the commonly used technique of pollen analysis could not be effectively employed. It has traditionally been used to indicate changing patterns of vegetation in response to sea-level change and to provide an independent age determinant, but before it can be utilized a comprehensive key to the pollen taxa of coastal Rio de Janeiro State is needed, and the analysis of fossil pollen assemblages on a spatial and temporal scale, sufficient to establish any regionally synchronous vegetation changes, must be undertaken. However, the destruction of most of the native vegetation in the coastal area during the past 200 years means that it may not be possible to collect appropriate type material to facilitate the identification of fossil pollen taxa. In addition, the problems of recognizing the regional pollen component in the tropics, where local pollen rain dominates and there is low pollen productivity, suggest that, even if synchronous vegetation changes have occurred, they will not be readily identified from fossil pollen records.

This methodology seems to be as successful, if not more successful than most of the methodologies which have been previously applied to the study of Brazilian sea-level change, although it has different strengths. When compared with the index points produced using the fossil-based approach of van Andel and Laborel (1964), the *Turfa herbacea* index points identified in this study are less altitudinally reliable. This is likely to remain a serious limitation where coastal sedimentary sequences are dominated by fine clastics and where no Basis Peat is found lying over an incompressible substratum. Nevertheless, the use of this methodology complements the fossil-based approach and has facilitated the recognition of sea-level tendencies on a shorter time-scale than was hitherto possible.

6.4 Future research

There are two lines of future research which would be of particular value in refining our knowledge of sea-level changes along the Brazilian coast.

Firstly, there is a need to re-examine, in detail, the evidence for a sea-level high at *c.* 5200 BP in all regions. The lack of detailed, published descriptions of the terrace levels means that a detailed field survey needs to be carried out seeking positive confirmation that they are of Holocene age and, if they are to be compared to a geoid surface which is related to MSL-Imbituba, levelling the terraces with respect to the national datum.

Secondly, in order to permit inter-regional comparison of sea-level tendencies of relatively short duration, the methodology employed in this study would need to be applied to other parts of the Brazilian coastline. This extension should include already studied areas such as São Paulo and Bahia States, but could be extended into states such as Espírito Santo which have not been studied to date. Indeed, the methodology could also be applied to other tropical coastlines.

Appendix I

Diatom floras used during diatom analysis

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Appendix II

Bacillariophyta (Diatoms) identified in the study

NAME OF TAXON	ABBREVIATION USED IN THE DIATOM DIAGRAMS	SALINITY GROUP
Achnanthes brevipes Agardh	Ac. brevipes	BM
A. hauckiana var. *genuina* A. Cleve	Ac. hauckiana v.g	B
A. hungarica Grunow	Ac. hungarica	FB
A. lanceolata (de Brébisson) Grunow	Ac. lanceolata	FB
Actinoptychus splendens (Shadbolt) Ralfs	Act. splendens	M
A. undulatus (Bailey) Ralfs	Act. undulatus	MB
Amphiprora alata Kützing	Amph. alata	MB
Amphora angusta var. *ventricosa* (Gregory) Cleve	Am. angusta v. ve	M
A. coffaeiformis var. *borealis* (Kützing) Cleve	Am. coffaeif v. bor	B
A. coffaeiformis var. *salina* (W. Smith) A. Cleve	Am. coffaeif v. sal	B
A. gigantea var. *typica* A. Cleve	Am. gigantea v.t	M
A. holsatica Hustedt	Am. holsatica	B
A. macilenta var. *typica* Cleve	Am. macilenta v.t.	MB
A. proteus var. *gregorii* A. Cleve	Am. proteus v. gr.	M
A. proteus var. *ocelata* Peragallo	Am. proteus v. oc.	M

Anomoeoneis sphaerophora (Kützing) Pfitzer	An. sphaerophora	FB-BF
Biddulphia pulchella Grey	Bi. pulchella	M
Campylodiscus clypeus Ehrenberg	Cam. clypeus	B
Cocconeis distans var. *bahusiensis* A. Cleve	Co. distans v. bah.	M
C. pediculus Ehrenberg	Co. pediculus	BF
C. placentula Ehrenberg	Co. placentula	FB
Coscinodiscus divisus Grunow	Cos. divisus	BM
C. lineatus var. *van heurckii* A. Cleve	Cos. lineatus v.h.	M
C. sublineatus Grunow	Cos. sublineatus	M
Cyclotella meneghiniana Kützing	Cy. meneghiniana	BF
C. striata var. *americana.* A. Cleve	Cy. striata v.am	M
Cymbella cuspidata Kützing	Cm. cuspidata	FB
C. ventricosa Kützing	Cm.ventricosa	*FB*
Dimerogramma marinum var. antiqua A. Cleve	Dim marinum v. an	M
D. minor var. *genuina* A. Cleve	Dim minor v. gen.	M
Diploneis boldtiana Cleve	D. boldtiana	F
D. bombus var. *egena* (A. Schmidt) Cleve	D. bombus v. egena	M
D. bombus var. *minor* Cleve	D. bombus v. minor	MB
D. incurvata (Gregory) Cleve	D. incurvata	M
D. ovalis (Hilse) Cleve	D. ovalis	FB
D. smithii (De Brébisson) Cleve	D. smithii	MB
Eunotia faba (Ehrenberg) Grunow	E. faba	F

E. faba var. *dense striata* Östrupi	E. faba v. dense	F
E. gracilis var. *genuina* A. Cleve	E. gracilis v. gen	F
E. major var. *indica* (Grunow) Å Berg	E. major v. indica	F
E. major var. *ventricosa* Cleve	E. major v. vent	F
E. monodon Ehrenberg	E. monodon	F
E. nymanniana var. *compacta* (Hustedt) A. Cleve	E. nymanniana v. c	F
E. parallela Ehrenberg	E. parallela	F
E. pectinalis (Dillwyn) Rabenhorst	E. pectinalis	F
E. pectinalis var. *elongata* van Heurck	E. pectinalis v.e	F
E. pectinalis var. *minor* (Kützing) Rabenhorst	E. pectinalis v.m	F
E. praebidens Å Berg	E. praebidens	F
E. praemonos Å Berg	E. praemonos	F
E. sarekensis Å Berg	E. sarekensis	F
E. sarekensis var *minor* (Hustedt) A. Cleve	E. sarekensis v.m	
E. tenella (Grunow) Hustedt	E. tenella	FB
E. tridon var. *genuina* A. Cleve	E. tridon v. gen	F
E. veneris (Kützing) O. Müller	E. veneris	F
Fragilaria brevistriata Grunow	Fg. brevistriata	FB
F. lapponica Grunow	Fg. lapponica	F
F. pinnata forma *subrotunda* Mayer	Fg. pinnata subr	FB
F. pinnata forma *subsolitaris* (Grunow) Mayer	Fg. pinnata subs	FB
F. pinnata forma *turgidula* (Schumann) A. Cleve	Fg. pinnata f. tu.	FB

Frustulia amphipleuroides var. *debilis* A. Cleve	F. amphipleuroid	F
F. rhomboides (Ehrenberg) De Toni	F. rhomboides	F
Gomphonema gracile Ehrenberg	G. gracile	FB
G. gracile var. *auritium* Å Berg	G. gracilis v.aur	FB
G. montanum Schumann	G. montanum	F
G. montanum var. *suecium* Grunow	G. montanum v.su	F
G. montanum var. *turriforme* A. Cleve	G. montanum v.tu	F
G. parvulum (Kützing) Grunow	G. parvalum	FB
G. turris (Ehrenberg) Grunow	G. turris	F
Grammatophora macilenta var. *nodulosa* Grunow	Gra. macilenta v.n	MB
Gyrosigma balticum (Ehrenberg) Cleve	Gy. balticum	B
Hantzschia amphioxys (Ehrenberg) Grunow	Hz. amphioxys	FB
Hyalodiscus subtilis Bailey	Hy. subtilis	M
Mastogloia braunii Grunow	Ma. braunii	B
M. elliptica (Agardh) Cleve	Ma. elliptica	B
M. lacustris var. *antiqua* (Schumann) A. Cleve	Ma. lacustris v.a.	BF
M. lanceolata Thwaites	Ma. lanceolata	MB
M. pumila (Grunow) Cleve	Ma. pumila	MB
Melosira ambigua (Grunow) O. Müller	Me. ambigua	FB
M. granulata (Ehrenberg) Ralfs	Me. granulata	FB
M. granulata var. *angustissima* O. Müller	Me. granulata v.a.	FB
M. granulata var. *typica* A. Cleve	Me. granulata v.t.	FB

M. islandica O. Müller	Me.islandica	F-FB
M. italica (Ehrenberg) Kützing	Me. italica	FB
Navicula amphipleuroides Hustedt	N. amphipleuroid	M
N. arvensis Hustedt	N. arvensis	F
N. brachium Hustedt	N. brachium	M
N cincta var. *typica* A. Cleve	N cincta v.typ.	FB
N. clamans Hustedt	N. clamans	B
N. cryptocephala Kützing	N. cryptocephala	F
N. dissipata Hustedt	N. dissipata	F
N. distans (W. Smith) A. Schmidt	N. distans	M
N. fossalis Krasske	N. fossalis	F
N. fruticosa Hustedt	N. fruticosa	FB
N.gracilis var. *schizonemoides* van Heurck	N.gracilis v. sch	FB
N. hungarica forma *elliptica* (Schultz) Östrupi	N. hungarica f.el	FB-F
N. insociabilis Krasske	N. insociabilis	F
N. lanceolata (Agardh) Kützing	N. lanceolata	FB
N. lyra Ehrenberg	N. lyra	M
N. molestiformis Hustedt	N. molestiformis	F
N. muraliformis Hustedt	N. muraliformis	F
N. muralis Grunow	N. muralis	F
N. mutica Kützing	N. mutica	BF
N. mutica forma *cohnii* (Hilse) Grunow	N. mutica f. cohn	BF

N. muticoides Hustedt	N. muticoides	F
N. oculiformis Hustedt	N. oculiformis	M
N. pelliculosa (De Brébisson) Hilse	N. pelliculosa	FB
N. pseudomuralis Hustedt	N. pseudomuralis	F
N. pupula var. *rectangularis* (Gregory) Grunow	N. pupula v. rect.	FB
N. salinarum Grunow	N. salinarum	B
N. scopularum De Brébisson	N. scopularum	M
N. strösei (Östrupi) A. Cleve	N. strosei	F-FB
N. terminata Hustedt	N. terminata	F
N. yarrensis Grunow	N. yarrensis	B
Nitzschia amphibia Grunow	Ni. amphibia	FB
N. amphibia var. *genuina* Mayer	Ni. amphibia v. ge	FB
N. angustata W. Smith	Ni. angustata	F
N. circumsuta (Bailey) Grunow	Ni. circumsuta	B
N. commutata var. *typica* A. Cleve	Ni. commutata v.ty	B
N. filiformis (W. Smith) Hustedt	Ni. filiformis	B
N. filiformis var. *ignorata* (Krasske) A. Cleve	Ni. filiformis v.i	F
N. frustulum (Kützing) Grunow	Ni. frustulum	BF
N. granulata Grunow	Ni. granulata	M
N. hantzschiana Rabenhorst	Ni. hantzschiana	F
N. microcephala Grunow	Ni. microcephala	FB
N. panduriformis var. *minor* Grunow	Ni.panduriformis	M

N. punctata (W. Smith) Grunow	Ni. punctata	BM
N. scalaris (Ehrenberg) W. Smith	Ni. scalaris	BF-FB
N. sigma (Kützing) W. Smith	Ni. sigma	BF
N. sigma var. *claussi* (Hantzsch) Grunow	Ni. sigma v. claus	BF
N. sigmoidea (Ehrenberg) W. Smith	Ni. sigmoidea	FB
N. spectabalis (Ehrenberg) Ralfs	Ni. spectabalis	*BF*
N. subtilis var. *genuina* Grunow	Ni. subtilis v.ge	F
N. thermalis var. *genuina* Mayer	Ni. thermalis v.g	FB
N. trybionella Hantzsch	Ni. trybionella	BF
Opephora marina var. *minuta* A. Cleve	Op. marina v.min.	M
O. pacifica (Grunow) Petit	Op. pacifica	M
O. parva (van Heurck) Krasske	Op. parva	M
Paralia sulcata (Ehrenberg) Cleve	Pa. sulcata	M
P. sulcata var. *biseriata* Grunow	Pa. sulcata v.bi	M
Pinnularia acrosphaeria (De Brébisson) W. Smith	P. acrosphaeria	F
P. borealis Ehrenberg	P. borealis	FB
P. divergentissima (Grunow) Cleve	P. divergentissima	F
P. lata (De Brébisson) W. Smith	P. lata	F
P. latevittata Cleve	P. latevittata	F
P. mesogongyla Cleve	P. mesogongyla	F
P. microstauron (Ehrenberg) Cleve	P. microstauron	F
P. parva var. *brevistriata* (Grunow) A. Cleve	P. parva v. brevi	F

P. stauroptera (Rabenhorst) Cleve	P. stauroptera	F
P. stauroptera var. *minuta* Mayer	P. stauroptera v.	F
P. subcapitata var. *stauroneiformis* van Heurck	P. subcapitata v.	F
P. sudetica Hilse	P. sudetica	F
P. viridis var. *genuina* A. Cleve	P. viridis v. gen.	FB
Plagiogramma staurophorum (Gregory) Heiberg	Pl. staurophorum	M
Pleurosigma elongatum W. Smith	Ple elongatum	BM
P. formosum var. genuinum A. Cleve	Ple. formosum v.g	M
P. normanii Ralfs	Ple. normanii	M
Rhabdonema minutum Kützing	Rhab. minutum	M
Rhaphoneis castracanii Grunow	Rhap. castracanii	M
Rhopalodia gibberula (Ehrenberg) O. Müller	Rh. gibberula	B
R. musculus (Kützing) O. Müller	Rh. musculus	B
Stauroneis gregorii forma *diminuta* Gregory	St. gregorii f. di	BM
S. phoenicenteron Ehrenberg	St. phoenicenteron	FB
Surirella ovalis var. crumena (De Brébisson) van Heurck	Su. ovalis v.cru	BM
S. ovata Kützing	Su. ovata	FB
Synedra tabulata (Agardh) Kützing	Sy. tabulata	BM
S. tabulata var. *affinis* (Kützing) A. Cleve	Sy. tabulata v. af.	BM
S. tabulata var. *grandis* (Mereschkowsky) Hustedt	Sy. tabulata v.gr.	BM
S. tabulata var. *obtusa* (Arnott) A. Cleve	Sy. tabulata v.ob.	BM
S. ulna (Nitzsch) Ehrenberg	Sy. ulna	FB

S. ulna var. *splendens* (Kützing) Brun	Sy. ulna v. splend	FB
Terpsinoë americana (Bailey) Ralfs	T. americana	B
T. musica Ehrenberg	T. musica	B-BF
Trachyneis aspera var. *pulchella* (W. Smith) Cleve	Tr. aspera v.pul	M

Appendix III

Stratigraphic descriptions and particle size analysis results for selected boreholes

Lagoa do Padre Site 1 Borehole 32

Grid Reference PQ30066002 Co-ordinates 22°57'03"S 42°45'22"W

Stratum	Height (metres)	Depth (metres)	Description
20	0.233 to 0.213	0.00 to 0.02	Th^{3}4 nig.3, strf.0, elas. 0, sicc.4, color 10 YR 3/3, struc. homog. and fibrous. A dark brown, well humified, herbaceous peat.
19	0.213 to -0.127	0.02 to 0.36	Ga2, As2, Ag+, Th^2+, Gs+, nig.3, strf.0, elas. 0, sicc. 3-2, color 7.5 YR 4/0 with 3Y4/1, struc. homog. and plastic, lim. sup. 1. A dark grey, silty, clayey sand with partly humified, herbaceous roots.
18	-0.127 to -0.747	0.36 to 0.98	Ga3, Gs1, Ag+, As+, Th^1+, nig.2, strf.0, elas. 0, sicc. 2, color 2.5 Y 4/0 with 2.5 Y 6/2, struc. heterog. and coh., lim. sup. 2. A silty, clayey sand, mottled dark grey and light brownish grey, with slightly humified, herbaceous roots.
17	-0.747 to -0.967	0.98 to 1.20	Ga3, Gs1, Gg (min.)+, Gg (maj.)+, As+, [part. test. (moll.) 1], nig. 3, strf.0, elas. 0, sicc.2, color 2.5 Y 4/0, struc. homog. and incoh., lim.sup.0. A dark grey, clayey, gravelly sand with single valves and fragments of *Anomalocardia brasiliana* (Gmelin)
16	-0.967 to -1.057	1.20 to 1.29	Ga4, Gs+, [part.test. (moll.) 4], nig. 3, strf.0, elas. 0, sicc.2, color 2.5 Y 4.5/0, struc. homog. and incoh., lim. sup. 0.

			A dark grey, clayey sand with single valves and fragments of *Anomalocardia brasiliana* (Gmelin)
15	-1.057 to 1.287	1.29 to 1.52	Ga4, Gs+, Ag+, [part. test. (moll.) +], nig. 3, strf.0, elas. 0, sicc. 2 color 2.5 Y 4/0, struc. heterog.: coh. to plastic, lim. sup. 1.
			A dark grey, clayey, silty sand with *Anomalocardia brasiliana* (Gmelin) fragments
14	-1.287 to -1.377	1.52 to 1.61	Ga3, As1, Ga+, Sh+, Dh+, nig. 3, strf.0, elas. 0, sicc.2, color 3Y 4/0, struc. homog. and plastic, lim. sup. 2.
			A dark grey, clayey sand with herbaceous plant fragments and decomposed organic matter.
13	-1.377 to -1.437	1.61 to 1.67	Ga4, As+, [part. test. (moll.) +], nig. 2-3, strf.1, elas. 0, sicc.2, color 2.5 Y 4/0, struc. heterog.: coh. to incoh., lim-sup.2.
			A dark grey, clayey sand with *Anomalocardia brasiliana* (Gmelin) fragments. There are lenses with increased clay content.
12	-1.437 to -1.577	1.67 to 1.81	Ga3, As1, Ag+, Sh+, [part.test. (moll.) +], nig. 3, strf.0, elas. 0,sicc.2, color 2.5 Y 4/0, struc. heterog. and plastic, lim. sup. 2.
			A dark grey, silty, clayey sand with decomposed organic matter and *Anomalocardia brasiliana* (Gmelin) fragments.
11	-1.577 to -1.617	1.81 to 1.85	Ga4, Gs+, Gg (min.) +, nig. 1, strf.0, elas. 0, sicc.2, color 2.5 Y 6/1, struc. homog. and incoh., lim. sup. 3.
			A light brownish grey, gravelly sand.

10	-1.617 to -1.657	1.85 to 1.89	Ga2, As1, Ag1, Sh +, [part.test. (moll.) +], nig. 3, strf.0, elas. 0, sicc.2, color 2.5 Y 4/0, struc. heterog. and plastic, lim. sup. 2, A dark grey, silty, clayey sand with decomposed organic matter, and single valves and fragments of *Anomalocardia brasiliana* (Gmelin)
9	-1.657 to -1.757	1.89 to 1.99	Ga4, Gs +, [part.test. (moll.) +], nig. 2, strf.0, elas. 0, sicc.2, color 2.5 Y 5/0, struc. heterog. and coh., lim. sup.1. A grey sand with single valves and fragments of *Anomalocardia brasiliana* (Gmelin) and small conical gastropod shells, possibly *Littoridina* Eydoux and Souleyet.
8	-1.757 to -1.857	1.99 to 2.06	Ga2, As1, Sh1, Ga +, nig. 3, strf.1, elas. 0, sicc.2, color 7.5 YR 4/0, struc. homog. and plastic., lim. sup. 1. A dark grey, clayey sand with decomposed organic matter and pockets of pure sand.
7	-1.827 to -1.857	2.06 to 2.09	$Ld^{3}3$, As1, Dh +, Dg +, nig. 3, strf.1, elas. 0, sicc.2, color 2.5 Y 3/2, struc. homog. and plastic, lim. sup. 3. A very dark greyish brown, clayey, fine detrital mud with fine plant fragments and herbaceous detritus.
6	-1.857 to -2.377	2.09 to 2.61	As2, Sh1, Ga1, Ga +, Ld^{3} +, Dg +, nig. 3, strf.1, elas. 0, sicc.2, color 7.5 YR 3.5 /0, struc. heterog.: plastic to incoh., lim. sup. 3. A dark grey, sandy, muddy clay with inclusion of pure sand and fine detrital mud with fine plant fragments.
5	-2.377 to	2.61 to	$Ld^{3}3$, As1, Th^{2} +, Ga +, nig. 2, strf.1, elas. 0, sicc.2,

	-2.387	2.62	color 2.5 Y 3/2, struc. homog. and plastic, lim. sup. 1.
			A very dark greyish brown, clayey, fine detrital mud with sand and partly humified, herbaceous roots.
4	-2.387 to -2.697	2.62 to 2.93	$Th^4$4, D1 +, Dh +, Ga +, nig. 4, strf.0, elas. 0, sicc.2, color 10 YR 2/2, struc. homog. and coh., lim. sup.O.
			A very dark brown, well humified, woody, herbaceous peat with sand.
3	-2.697 to -3.547	2.93 to 3.78	Ga2, Gsl, Asl, nig. 2-3, strf.0, elas. 0, sicc.2, color 10 YR 5/1 with 10 YR 4/1, struc. homog. and coh., lim. sup. 3
			A clayey sand mottled grey and dark grey
	-3.547 to -3.667	3.78 to 3.90	Ga4, Gs +, As +, nig. 1, strf.0, elas. 0, sicc.2, color 10 YR 7/1, struc. homog. and coh., lim. sup. 2.
			A light grey, clayey sand with flakes of biolite mica.
1	-3.667 to -4.107	3.90 to 4.34	As4, Ga +, Th^3 +, nig. 1, strf.0, elas. 0, sicc.2, color 10 YR 6/1, struc. homog. and plastic, lim. sup. 3.
			A light grey, very hard, sandy, kaolinitic clay with well humified, herbaceous roots.

Particle size analysis

Stratum	Depth (m)	Gravel (%)	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Medium silt (%)	Fine silt (%)	Clay (%)
19	0.17-0.21	0.00	5.03	42.75	6.90	2.01	5.60	7.37	30.35
18	0.05-0.54	0.00	18.02	75.97	3.56	1.67	0.00	0.00	0.77
18	0.80-0.84	0.66	16.22	78.27	2.48	1.10	0.76	0.00	0.51
17	1.07-1.11	0.00	17.30	78.78	2.07	0.75	0.00	0.00	1.10
16	1.23-1.27	0.25	8.64	78.52	8.56	1.49	0.00	0.85	1.69
15	1.39-1.43	0.00	3.97	62.97	13.99	4.47	1.79	3.59	9.23
14	1.55-1.59	0.00	5.59	63.00	8.14	4.96	0.00	0.00	18.32
13	1.62-1.66	0.00	6.26	74.50	10.97	1.76	0.52	1.56	4.43
12	1.72-1.76	0.07	4.78	52.53	15.48	3.88	1.92	3.83	17.52

Particle size analysis

Stratum	Depth (m)	Gravel (%)	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Medium silt (%)	Fine silt (%)	Clay (%)
11	1.81-1.85	0.01	7.73	85.92	4.73	0.34	0.26	0.26	0.77
10	1.85-1.89	0.00	3.38	41.98	15.05	7.99	3.85	5.49	22.25
9	1.92-1.96	9.66	7.32	67.60	8.00	1.41	0.26	1.57	4.19
8	2.00-2.04	0.00	2.79	35.04	16.04	6.58	15.48	6.02	18.06
7	2.06-2.09	1.30	10.88	35.72	14.42	14.24	10.78	5.16	7.50
6	2.20-2.24	0.00	3.67	34.29	8.37	20.41	2.77	9.24	21.25
6	2.47-2.51	0.00	0.78	10.44	4.05	30.70	19.68	13.60	20.75
3	3.12-3.16	1.46	20.67	55.54	5.57	1.81	2.10	1.57	11.28
3	3.55-3.59	5.40	20.93	50.91	7.29	0.18	3.76	1.61	9.93

Particle size analysis

Stratum	Depth (m)	Gravel (%)	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Medium silt (%)	Fine silt (%)	Clay (%)
2	3.82-3.86	0.00	6.68	81.67	3.59	0.91	0.77	1.53	4.85
1	4.10-4.14	0.00	0.54	4.66	1.07	3.82	15.93	1.62	72.36

Lagoa do Padre Site 2 Borehole 12

Grid Reference PQ27606093 Co-ordinates 22°56'34"S 42°46'54"W

Stratum	Height (metres)	Depth (metres)	Description
18	2.826 to 2.326	0.00 to 0.50	$Th^{3}4$, Dh+, Dl+, $Tl^{2}+$, nig. 4, strf. 1, elas. 1, sicc. 2, color 10 YR 2/2, struc. heterog.: coh. to incoh. A very dark brown, well humified, woody, herbaceous peat.
17	2.326 to 1.996	0.50 to 0.63	$Th^{4}4$, Dh+, nig. 4, strf. 0, elas. 0, sicc. 2, color 10 YR 2/2, struc. homog. and totally incoh., lim. sup.0. A very dark brown, humified, woody, herbaceous peat.
16	1.996 to 1.916	0.63 to 0.91	$Th^{3}4$, Dl+, Dh+, nig. 4, strf. 0, elas. 1, sicc. 2, color 10 YR 2/2, struc. homog. and coh., lim. sup. 0. A very dark brown, well humified, woody, herbaceous peat.
15	1.916 to 1.736	0.91 to 1.09	$Th^{1}4$, Dh+, Dl+, nig. 2, strf. 2, elas. 3, sicc. 2, color 10 YR 6/3 to 10YR 2/2, struc. homog. and felted, lim. sup. 1. A pale brown to very dark brown, slightly humified, woody, herbaceous peat.
14	1.736 to 1.336	1.09 to 1.49	$Th^{4}4$, nig. 4, strf. 0, elas. 0, sicc. 2, color 10 YR 2/1.5, struc. homog. and coh., lim. sup. 2. A very dark brownish black, humified, herbaceous peat.
13	1.336 to	1.49 to	As2, Ag1, $Ld^{3}1$, Ga+, $Tl^{2}+$, nig. 2, strf. 1, elas. 0, sicc. 2,

	1.036	1.79	color 10 YR 5/2, struc. homog. and plastic, lim. sup. 3. A greyish brown, silty clay with fine detrital mud, sand and partly humified, ligneous roots.
12	1.036 to 0.926	1.79 to 1.90	$Th^{4}4$, nig. 4, strf. 0, elas. 0, sicc. 2, color 10 YR 2/1.5, struc. homog. and coh., lim. sup. 3. A very dark brownish black, humified, herbaceous peat.
11	0.926 to 0.706	1.90 to 2.12	As2, Ag1, $Ld^{3}1$, Ga +, nig. 2, strf. 1, elas. 0, sicc. 2, color 10 YR 5/1, struc. homog. and plastic, lim. sup. 2. A grey, silty clay with fine detrital mud and sand
10	0.706 to 0.386	2.12 to 2.44	Ga2, Gs1, As1, nig. 2, strf. 0, elas. 0, sicc. 2, color 2.5 Y 5/2, struc. heterog.: incoh. to plastic, lim. sup. 1. A greyish brown, clayey sand
9	0.386 to 0.236	2.44 to 2.59	$Ld^{3}2$, As2, Ag +, Ga +, Tl^{2} +, nig. 2, strf. 1, elas. 0, sicc. 2, color 10 YR 4.5/2, struc. heterog. and plastic, lim. sup. 2. A greyish brown, silty, clayey, fine detrital mud with sand and partly humified, ligneous roots
8	0.236 to -0.044	2.59 to 2.87	$Ld^{3}2$, As1, Ag1, Ga +, Tl^{1} +, nig. 3, strf. 0, elas. 0, sicc. 2, color 2.5 Y 4/2, struc. homog. and plastic, lim. sup. 0. A dark greyish brown, silty, clayey, fine detrital mud with sand and slightly humified, fine ligneous roots
7	-0.044 to	2.87 to	Ag2, As1, Sh1, Tl^{1} +, Dl +, Dh +, Ga +, Gs +, Gg (min.) +,

	-0.994	3.82	nig. 3, strf. 1, elas. 0, sicc. 2, color 2.5 Y 3.5/0, struc. heterog. and plastic., lim. sup.3. A very dark grey, muddy, clayey silt with slightly humified, fine ligneous roots, herbaceous and woody plant fragments and inclusions of pure sand and fine gravel.
6	-0.994 to -1.584	3.82 to 4.41	Ag2, As1, Sh1, Tl^1+, Dl+, Dh+, Ga+, Gs+, [part. test. (moll.) +], nig. 3, strf. 0, elas. 0, sicc. 2, color 2.5 Y 3.5/0, struc. heterog. and plastic., lim. sup.0. A very dark grey, muddy, clayey silt with slightly humified, fine ligneous roots, herbaceous and woody plant fragments, *Anomalocardia brasiliana* (Gmelin) fragments and inclusions of pure sand.
5	-1.584 to -1.674	4.41 to 4.50	Ga3, Ag1, Gs+, Gg (min.)+, Tl^1+, nig. 2, strf. 0, elas. 0, sicc. 2, color 2.5 Y 5/0, struc. homog. and incoh., lim. sup.2. A grey, silty sand with fine gravel and slightly humified, fine, ligneous roots.
4	-1.674 to -1.864	4.50 to 4.69	As3, Sh1, Tl^1+, Ag+, Ga+, Gs+, nig. 3, strf. 0, elas. 0, sicc. 2, color 2.5 Y 3.5/0, struc. heterog. and plastic., lim. sup. 3. A very dark grey, muddy clay with slightly humified, fine ligneous roots, silt and inclusions of pure sand.
3	-1.864 to -1.964	4.69 to 4.74	As2, $Ld^3$2, Dh+, Th^2+, Ag+, nig. 3, strf. 0, elas. 0, sicc. 2, color 2.5 Y 3/2, struc. homog. and plastic, lim. sup. 2. A very dark greyish brown, muddy clay with partly humified, herbaceous roots, plant fragments and silt.

2	-1.964 to -2.774	4.74 to 5.60	Ga2, Gs2, Gg (min.)+, Gg (maj.)+, Dl+, nig. 2, strf. 0, elas. 0, sicc. 2, color 5 Y 5/1, struc. homog. and incoh., lim. sup. 3. A grey, gravelly sand with woody plant fragments.
1	-2.774 to -2.904	5.60 to 5.73	Ga2, Gs2, Gg (min.)+, Gg (maj.)+, Dl+, As+, nig. 2, strf. 0, elas. 0, sicc. 2, color 10 YR 5/1.5, struc. homog. and slightly incoh., lim. sup. 1. A brownish grey, gravelly sand with woody plant fragments and clay.

Particle size analysis

Stratum	Depth (m)	Gravel (%)	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Medium silt (%)	Fine silt (%)	Clay (%)
13	1.62-1.66	0.11	3.47	21.60	6.83	6.08	4.72	7.50	49.69
11	1.99-2.03	0.05	8.12	28.12	7.26	6.07	3.25	5.42	41.72
10	2.25-2.29	0.31	20.73	40.54	8.87	5.39	2.34	2.34	19.49
9	2.51-2.55	0.51	17.37	40.89	7.40	4.27	4.59	7.46	17.50
8	2.71-2.75	0.00	0.98	1.25	0.36	18.99	14.42	21.18	42.81
7	3.09-3.13	0.00	5.50	20.92	9.69	9.99	17.27	14.29	22.33
7	3.35-3.39	0.17	6.26	22.03	14.43	17.96	12.85	10.22	16.06
7	3.56-3.60	0.00	0.46	4.88	8.71	25.02	20.97	16.38	23.59
6	4.00-4.04	0.00	0.57	4.07	9.29	24.48	18.92	16.36	26.30

Particle size analysis

Stratum	Depth (m)	Gravel (%)	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Medium silt (%)	Fine silt (%)	Clay (%)
6	4.19-4.23	0.00	0.45	9.25	24.33	15.95	12.29	19.43	18.29
5	4.44-4.48	0.91	4.61	33.17	37.17	8.83	1.62	2.70	10.79
3	4.70-4.74	0.00	9.48	37.45	12.48	12.20	10.00	5.81	12.58
2	5.04-5.08	5.11	36.67	45.83	10.62	1.26	0.51	0.00	0.00
2	5.31-5.35	5.96	45.81	41.67	5.66	0.91	0.00	0.00	0.00
1	5.65-5.69	2.56	32.21	37.58	12.58	5.55	2.06	1.55	5.92

Itaipu-Açu Site 1 Borehole 3

Grid Reference PQ08055916 Co-ordinates 22°57'48"S 42°54'20"W

Stratum	Height (metres)	Depth (metres)	Description
9	5.553 to 5.132	0.00 to 0.42	Stratum confusum
8	5.132 to 5.063	0.42 to 0.49	Ga2, Gs2, Gg (min.) +, Thl +, nig. 1, strf. 0, elas. 0, sicc. 3, color 10 YR 7/1, struc. homog.and incoh., lim. sup. 3. A light grey, gravelly sand with slightly humified, herbaceous roots.
7	5.063 to 5.013	0.49 to 0.54	Ga2, Gs2, Ag +, As +, Sh +, nig. 4, strf. 0, elas. 0, sicc. 2, color 10 YR 2/2 to 10 YR 7/1, struc. heterog.: plastic to incoh.,lim sup. 1. A clayey, silty sand with organic matter; mottled very dark brown and light grey.
6	5.013 to 4.943	0.54 to 0.61	Gs2, Ga2, Gg (min.) +, Sh +, nig. 1, strf. 0, elas. 0, sicc. 2, color 10 YR 7/1, struc. homog.and incoh., lim. sup. 0. A light grey, gravelly sand with organic matter.
5	4.943 to 4.863	0.61 to 0.69	Th34, nig. 4, strf. 0, elas. 1, sicc. 2, color 10 YR 2/2, struc. homog. and coh., lim.sup. 3. A very dark brown, well humified herbaceous peat.
4	4.863 to 4.823	0.69 to 0.73	Sh2, As2, anth. +, nig. 4, strf. 0, elas. 0, sicc. 2, color 10 YR 2/1, struc. homog. and coh., lim.sup. 2. Black, clayey organic matter with charcoal fragments

3	4.823 to 4.763	0.73 to 0.79	As2, ShAs2, Ag+, nig. 4, strf. 0, elas. 0, sicc. 2, color 10 YR 2/1, struc. homog. and coh., lim.sup. 1. A black, silty, organic clay.
2	4.763 to 4.273	0.79 to 1.28	Ga2, Gs2, Ag+, As+, Sh+, nig. 4, strf. 0, elas. 0, sicc. 2, color 10 YR 2/1.5, struc. homog. and incoh., lim. sup. 3. A very dark brown, clayey, silty sand with organic matter
1	4.273 to 4.533	1.28 to 1.54	Gs2, Gs2, Gg (min.)+, nig. 2, strf. 0, elas. 0, sicc. 2, color 10 YR 4/1, struc. homog. and incoh., lim. sup. 2. A dark grey, gravelly sand of subrounded quartz.

Particle size analysis

Stratum	Depth (m)	Gravel (%)	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Medium silt (%)	Fine silt (%)	Clay (%)
8	0.44-0.48	0.00	48.39	47.33	1.51	2.77	0.00	0.00	0.00
7	0.50-0.54	0.00	48.60	44.94	1.59	1.67	0.80	1.07	1.33
6	0.56-0.60	0.00	47.15	50.63	1.56	0.40	0.25	0.00	0.00
2	0.93-0.97	0.10	38.21	48.64	3.34	4.79	1.55	0.78	2.59
2	1.10-1.14	0.15	30.98	62.47	2.81	1.26	0.26	0.52	1.55
1	1.38-1.42	0.35	38.55	60.20	0.40	0.00	0.00	0.00	0.51

Itaipu-Açu Site 2 Borehole 12

Grid Reference	PQ05455884		Co-ordinates 22°57'01"S 42°59'44"W
Stratum	Height (metres)	Depth (metres)	Description
14	1.285 to 0.945	0.00 to 0.34	Ga2, Gs1, $Th^4$1, Gg (min.) +, Th^1 +, nig. 2-4, strf. 0, elas. 0, sicc. 4-3, color 10 YR 3/2.5 to 10 YR 2/2, struc. homog.: coh. to incoh.. A dark brown to very dark brown, peaty sand with fine gravel and slightly humified, herbaceous roots.
13	0.945 to 0.465	0.34 to 0.82	$Th^4$2, As2, Ga +, nig. 4, strf. 0, elas. 0, sicc. 3-2, color 10 YR 2/2, struc. homog. and plastic, lim. sup.1. A very dark brown, clayey, well humified, herbaceous peat with a trace of sand.
12	0.465 to 0.295	0.82 to 0.99	$Th^4$4, Dl +, Tl +, nig. 4, strf. 0, elas. 0, sicc. 2, color 10 YR 2/2, struc. homog. and plastic, lim. sup.1. A very dark brown, well humified, herbaceous peat with woody roots and detritus.
11	0.295 to 0.175	0.99 to 1.11	$Ld^3$2, As1, Ga1, Gs +, Gg (min.) +, Th^2 +, nig 3, strf. 1, elas. 1, sicc. 2, color 2.5 Y 3/2, struc. homog. and plastic, lim. sup. 1. A very dark greyish brown, sandy, clayey, fine detrital mud with partially humified, herbaceous roots.
10	0.175 to 0.045	1.11 to 1.24	As2, Ga1, Sh1, Tl^2 +, Gs +, nig. 3, strf. 0, elas. 0, sicc. 2, color 7.5 YR 4/0, struc. homog. and plastic, lim. sup. 2.

			A dark grey, sandy, muddy clay with partly humified, woody roots.
9	0.045 to -0.055	1.24 to 1.34	Ld^{3}3, As1, Ga +, Th^{2} +, Gs +, nig. 3, strf. 1, elas. 0, sicc. 2, color 2.5 Y 3/2, struc. homog. and plastic, lim. sup. 2.
			A very dark greyish brown, sandy, clayey fine detrital mud with partially humified, herbaceous roots.
8	-0.055 to -1.025	1.34 to 2.31	As2, Ga1, Sh1, Tl^{1} +, Th^{2} +, Gs +, Ld^{3} +, nig 3, strf. 0, elas. 0, sicc. 2, color 7.5 YR 4/0, struc. heterog. and plastic, lim. sup. 2.
			A dark grey, sandy, muddy clay with woody and herbaceous roots.
7	-1.025 to -1.075	2.31 to 2.36	As2, Ld^{3}2, Ga +, nig. 3, strf. 2, elas. 1, sicc. 2, color 10 YR 3/2, struc. homog. and coh., lim. sup. 1.
			A very dark greyish brown, sandy, clayey, fine detrital mud.
6	-1.075 to -1.305	2.36 to 2.59	As3, Sh1, Ga +, Gs +, nig. 3, strf. 0, elas. 0, sicc. 2, color 7.5 YR 4/0, struc. homog. and plastic, lim. sup. 1.
			A dark grey, sandy, muddy clay.
5	-1.305 to -1.495	2.59 to 2.78	Ga3, Gs1, Gg (min.) +, Sh +, As +, [part. test. (moll.) 1], nig. 2-3, strf. 0, elas. 0, sicc. 2. color 7.5 YR 4/0 to 7.5 YR 6/0, struc. heterog.: incoh. to plastic, lim. sup. 2.
			A grey to dark grey, clayey, muddy, gravelly sand with single valves and fragments of *Anomalocardia brasiliana* (Gmelin).
4	-1.495 to	2.78 to	Gs3, Ga1, Gg (min.) +, nig. 2, strf. 0, elas. 0, sicc. 2,

	-1.655	2.94	color 5 Y 5/2., struc. heterog. and incoh., lim. sup. 1. An olive grey sand with gravel.
3	-1.655 to -1.955	2.94 to 3.24	Gs2, Ga1, Gg (min.)1, Gg (maj.) + nig. 2, strf. 0, elas. 0, sicc. 2, color 5 Y 5/2, struc. homog. and incoh., lim. sup. 0. An olive grey, gravelly sand.
2	-1.955 to -2.215	3.24 to 3.50	Ga3, Gs1, Gg (min.) +, nig. 1, strf. 0, elas. 0, sicc. 2, color 2.5 Y 6/2, struc. homog. and incoh., lim. sup. 2. A light brownish grey sand with gravel.
1	-2.215 to -2.465	3.50 to 3.75	Gs2, Ga1, Gg (min.)1, nig. 3, strf. 0, elas. 0, sicc. 2, color 2.5 Y 4/2, struc. homog. and incoh., lim. sup. 1. A dark greyish brown, gravelly sand.

Particle size analysis

Stratum	Depth (m)	Gravel (%)	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Medium silt (%)	Fine silt (%)	Clay (%)
14	0.15-0.19	0.21	37.19	55.11	3.93	0.44	0.52	0.52	2.08
11	1.00-1.10	1.08	11.39	19.29	5.74	12.67	21.36	11.73	16.75
10	1.15-1.21	0.30	7.58	28.08	6.79	13.01	14.54	11.21	18.48
9	1.26-1.32	0.07	14.61	31.54	4.03	8.15	16.16	10.66	14.79
8	1.50-1.57	0.00	4.86	2.76	0.73	16.76	49.69	14.25	10.76
8	1.70-1.75	0.00	8.05	42.37	8.17	7.19	10.90	5.45	17.86
8	1.90-1.96	0.00	4.91	33.02	5.66	10.35	16.61	8.77	20.68
8	2.10-2.14	0.06	7.18	45.08	12.33	5.14	5.13	10.26	14.82
7	2.31-2.35	0.00	2.83	15.25	7.56	8.35	17.35	17.97	30.68

Particle size analysis

Stratum	Depth (m)	Gravel (%)	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Medium silt (%)	Fine silt (%)	Clay (%)
6	2.44-2.52	0.89	9.07	13.91	7.16	11.97	22.32	13.74	20.95
5	2.67-2.71	0.51	27.22	59.43	8.80	0.54	0.64	0.64	2.23
4	2.84-2.88	10.47	59.56	28.66	1.01	0.05	0.00	0.00	0.25
3	3.07-3.11	30.64	56.42	12.14	0.80	0.00	0.00	0.00	0.00
2	3.35-3.39	6.60	33.77	58.06	1.56	0.00	0.00	0.00	0.00
1	3.61-3.65	15.12	62.87	17.40	4.25	0.10	0.00	0.00	0.25

Lagoa de Itaipú Site 1 Borehole 33

Grid Reference PQ01445966 Co-ordinates 22°57'31"S 43°02'07"W

Stratum	Height (metres)	Depth (metres)	Description
19	0.49 to 0.03	0.00 to 0.46	$Th^{3}4$, nig. 4, strf. 0, elas. 1, sicc.2, color 10 YR 2/1.5, struc. homog. and fibrous. A very dark brown, partly humified, herbaceous peat.
18	0.03 to -1.19	0.46 to 1.68	As3, Ag1, Ga1, $Th^{2}+$, Sh +, nig. 3, strf. 0, elas. 0, sicc.2, color 7.5 YR 3.5/0, struc. homog. and plastic, lim. sup. 0. A very dark grey, muddy, silty clay with small traces of fine and medium sand and fine, partly humified, herbaceous roots.
17	-1.19 to -1.53	1.68 to 2.02	As2, Ag2, Sh +, $Th^{2}+$, Ga +, nig. 3, strf. 0, elas. 0, sicc.2, color 10 YR 2/2, struc. homog. and plastic, lim. sup. 0. A very dark brown, muddy, silty clay with small lenses of fine and medium sand and with fine, partly humified, herbaceous roots.
16	-1.53 to -1.79	2.02 to 2.28	$Th^{4}4$, $Tl^{3}+$, Dl +, nig. 4, strf. 0, elas. 0, sicc.2, color 10 YR 2/2, struc. homog. and coh., lim. sup. 2. A very dark brown, woody, herbaceous peat.
15	-1.79 to -1.93	2.28 to 2.42	Sh4, Dl +, nig. 4, strf. 0, elas. 0, sicc.2, color 10YR 2/2, struc. homog. and coh., lim. sup. 0. Very dark brown, woody, humified organic matter.

14	-1.93 to -2.04	2.42 to 2.53	As2, Ag2, Sh+, Tl^1+, nig. 4, strf. 0, elas. 0, sicc.2, color 10YR 2/1, struc. homog. and plastic., lim. sup. 0. A black, organic, silty clay with slightly humified, ligneous roots.
13	-2.04 to -2.45	2.53 to 2.94	As4, Ag+, Ld^3+, Th^3+, Tl^3+, nig. 3, strf. 0, elas. 0, sicc.2, color 10 YR 5/1, struc. homog. and plastic, lim. sup. 1. A grey, muddy, silty clay with well humified, woody and herbaceous roots.
12	-2.45 to -2.65	2.94 to 3.14	As3, Ag1, Tl^1+, anth.+, (+Lso?), nig. 2, strf. 0, elas. 0, sicc.2, color 10 YR 5.5/4, struc. homog. and plastic, lim. sup. 2. A light yellowish brown, silty clay with slightly humified, ligneous roots, charcoal fragments and a possible siliceous mud fraction.
11	-2.65 to -2.67	3.14 to 3.16	As4, Ag+, Sh+, nig. 4, strf. 0, elas. 0, sicc.2, color 2.5Y 2/0, struc. homog. and plastic, lim. sup. 1. A black, silty clay with an organic fraction.
10	-2.67 to -2.72	3.16 to 3.21	As4, Ag+, Ld^3+, Tl^1+, nig. 2, strf. 0, elas. 0, sicc.2, color 2.5Y 4.5/2, struc. homog. and plastic, lim. sup. 1. A greyish brown, muddy, silty clay with slightly humified, ligneous roots.
9	-2.72 to -2.78	3.21 to 3.27	As4, Ag+, Th^2+, (+Lso?), nig. 2, strf. 0, elas. 0, sicc.2, color 10 YR 6/3, struc. homog. and plastic, lim. sup. 2.

			A pale brown, silty clay with partly humified, herbaceous roots and a possible siliceous mud fraction.
8	-2.78 to -2.80	3.27 to 3.29	As4, Ag+, Sh+, nig. 4, strf. 0, elas. 0, sicc.2, color 2.5Y 2/0, struc. homog. and plastic, lim. sup. 1.
			A black, silty clay with an organic fraction.
7	-2.80 to -2.91	3.29 to 3.40	As4, Ag+, Ld^3+, nig. 3, strf. 0, elas. 0, sicc.2, color 10 YR 4.5/1, struc. homog. and plastic, lim. sup. 2.
			A dark grey, muddy, silty clay.
6	-2.91 to -3.52	3.40 to 4.01	$Ld^3$2, As1, Ag1, Dh+, (+Lso?), nig. 3, strf. 0, elas. 0, sicc.2, color 2.5Y 3/2, struc. heterog. and slightly plastic, lim. sup. 2.
			A very dark greyish brown, silty, clayey mud with herbaceous plant fragments and a possible siliceous mud fraction.
5	-3.52 to -4.15	4.01 to 4.64	$Th^4$4, Tl^2+, anth.+, nig. 4, strf. 0, elas. 0, sicc.2, color 10YR 2/2, struc. homog. and coh., lim. sup. 4.
			A very dark brown, woody, herbaceous peat with charcoal fragments.
4	-4.15 to -4.34	4.64 to 4.83	Ag3, As1, (+Lso?), Tl^2+, Th^2+, nig. 2, strf. 0, elas. 0, sicc.2, color 10 YR 7/4 mottled with 10 YR 6/3, struc. heterog. and plastic, lim. sup. 2.
			A very pale brown and pale brown clayey silt with partly humified, ligneous and herbaceous roots and a possible siliceous mud fraction.
3	-4.34 to	4.83 to	anth. 4, As+, nig. 4, strf. 0, elas. 0, sicc.2,

	-4.36	4.85	color 2.5Y 2/0, struc, homog. and incoh., lim. sup. 3. Black, angular charcoal fragments with a trace of clay.
2	-4.36 to -5.61	4.85 to 6.10	$Th^4 4$, $Tl^3 +$, Dh +, nig. 4, strf. 0, elas. 0, sicc.2, color 10 YR 2/2, struc. homog. and coh., lim. sup. 2. A very dark brown, humified, woody, herbaceous peat.
1	-5.61 to 5.87	6.10 to 6.36	Ag2, Ga1, $Ld^3 1$, Gs +, As +, $Th^4 +$, nig. 3, strf. 1, elas. 0, sicc.2, color 10 YR 4/3, struc. homog. and plastic, lim. sup. 2. A brown, clayey, muddy, sandy silt with lenses of humified herbaceous peat.

Particle size analysis

Stratum	Depth (m)	Gravel (%)	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Medium silt (%)	Fine silt (%)	Clay (%)
18	0.61-0.65	0.00	0.63	5.50	4.17	15.81	9.24	10.83	53.82
18	1.07-1.11	0.00	1.02	10.47	5.60	5.61	10.61	12.73	53.96
18	1.37-1.41	0.00	0.18	2.68	3.16	8.11	12.88	10.73	62.25
17	1.83-1.87	0.00	0.26	6.41	8.83	13.98	14.83	10.22	45.47
14	2.46-2.50	0.00	0.12	0.17	0.23	9.20	18.76	14.65	56.86
13	2.72-2.76	0.00	0.42	0.94	0.84	3.88	5.26	2.63	86.03
12	3.02-3.06	0.00	0.33	0.47	0.40	9.73	11.76	10.76	66.55
11	3.14-3.16	0.00	0.34	0.45	0.45	3.46	2.85	4.85	87.59
10	3.17-3.21	0.00	0.36	0.48	0.42	0.56	2.40	0.60	95.18

Particle size analysis

Stratum	Depth (m)	Gravel (%)	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Medium silt (%)	Fine silt (%)	Clay (%)
9	3.22-3.26	0.00	0.36	0.43	0.36	0.47	3.37	3.68	91.33
8	3.27-3.29	0.00	0.07	0.27	0.14	0.47	1.71	5.12	92.23
7	3.33-3.37	0.00	0.05	0.05	0.05	0.23	1.10	2.48	96.02
6	3.58-3.62	0.00	2.60	3.45	1.51	8.06	21.02	17.36	46.00
6	3.79-3.83	0.00	1.65	3.54	1.83	7.47	19.99	13.84	51.68
4	4.72 4.76	0.00	0.36	1.14	1.02	17.98	34.33	21.08	24.09
1	6.21 6.25	0.08	9.04	23.47	9.52	13.14	17.98	8.79	17.98

Lagoa de Itaipú Site 2 Borehole 26

Grid Reference NQ99985973 Co-ordinates 22°57'30"S 43°02'58"W

Stratum	Height (metres)	Depth (metres)	Description
12	0.616 to 0.486	0.00 to 0.13	As2, Ag1, Ga1, Th2+, Sh+, nig.3, strf.0, elas. 0, sicc. 2, color 10 YR 3/2, struc. homog. and plastic. A very dark greyish brown, sandy, clayey silt with organic matter and partly humified, herbaceous roots.
11	0.486 to 0.456	0.13 to 0.16	Ga2, Ag1, As1, Gs+, Sh+, Th2+, nig.3, strf.0, elas. 0, sicc. 2, color 10 YR 4/2, struc. homog. and slightly plastic, lim. sup. 0. A dark greyish brown, clayey, silty sand with organic matter.
10	0.456 to -0.184	0.16 to 0.80	As2, Ag2, Ga+, Sh+, Dl+, nig.3, strf.0, elas. 0, sicc. 2, color 10 YR 3/2, struc. homog. and plastic, lim. sup.0. A very dark greyish brown, silty clay with sand, organic matter and woody detritus.
9	-0.184 to -1.744	0.80 to 2.36	As2, Ag2, Ga+, Gs+, nig.3, strf.0, elas. 0, sicc. 2, color 7.5 YR 3.5/0, struc. homog. and plastic, lim. sup. 1. A dark grey, sandy, silty clay.
8	-1.744 to -1.894	2.36 to 2.51	As2, Ag2, Sh+, Ga+, nig.3, strf.0, elas. 0, sicc. 2, color 10 YR 3/1.5, struc. homog. and plastic, lim. sup. 0. A very dark greyish brown, sandy, silty clay with organic matter.
7	-1.894 to	2.51 to	Ga2, As1, Ag1, Sh+, Dl+, nig.3, strf.0, elas. 0, sicc. 2,

	-1.944	2.56	color 10 YR 3/2, struc. homog. and slightly plastic, lim. sup. 1. A very dark greyish brown, silty, clayey sand with organic matter and woody detritus.
6	-1.944 to -2.394	2.56 to 3.01	Th^{4}4, Dl+, Tl^3+, nig.4, strf.0, elas. 1, sicc. 2, color 10 YR 2/2, struc. homog. and coh., lim. sup. 2. A very dark brown, humified, woody, herbaceous peat.
5	-2.394 to -2.574	3.01 to 3.19	Ag3, Sh1, As+, nig.4, strf.0, elas. 0, sicc. 2, color 10 YR 2/1, struc. homog. and plastic, lim. sup. 2. A black clayey, organic silt.
4	-2.574 to -2.714	3.19 to 3.33	Ag3, Ld^{2}1, As+, nig.1, strf.0, elas. 0, sicc. 2, color 10 YR 7/3, struc. homog. and slightly plastic, lim. sup. 2. A very pale brown, clayey, muddy silt.
3	-2.714 to -3.474	3.33 to 4.09	Ag3, Ld^{3}1, As+, nig.3, strf.0, elas. 0, sicc. 2, color 10 YR 4/2, struc. heterog.: granular and plastic, lim. sup. 0. A dark greyish brown, clayey, muddy silt
2	-3.474 to -4.324	4.09 to 4.94	Th^{4}4, Dl+, nig.4, strf.0, elas. 0, sicc. 2, color 10 YR 2/2, struc. homog. and coh., lim. sup. 1. A very dark brown, humified, woody, herbaceous peat.
1	-4.324 to -4.484	4.94 to 5.10	Ag3, As1, Sh+, Ga+, Tl^2+, nig.3, strf.1, elas. 0, sicc. 2, color 10 YR 4/2, struc. homog. and plastic, lim. sup. 2.

A dark greyish brown, sandy, clayey silt with organic matter and woody roots.

Particle size analysis

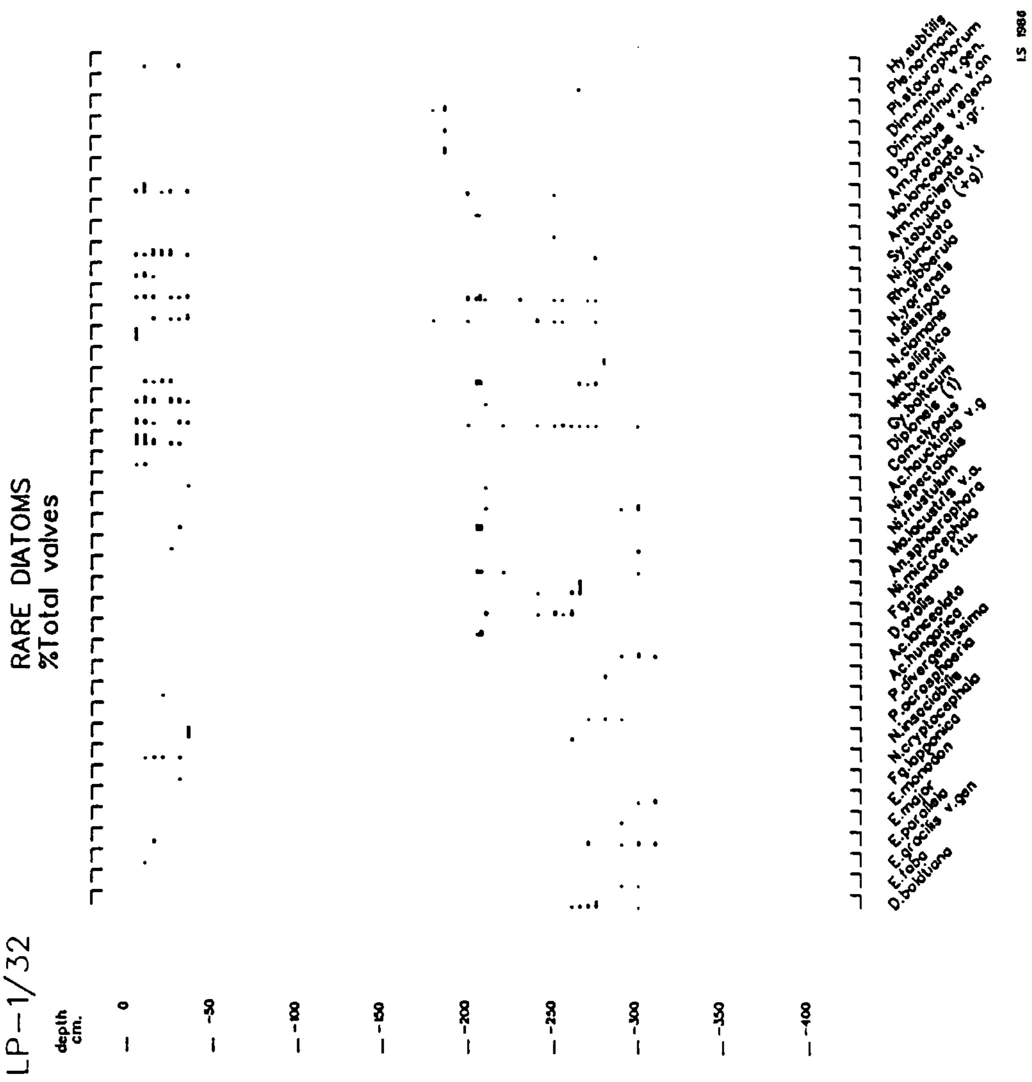
Stratum	Depth (m)	Gravel (%)	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Medium silt (%)	Fine silt (%)	Clay (%)
12	0.05-0.10	0.00	0.47	23.27	6.80	9.80	12.99	9.75	36.92
11	0.13-0.16	0.00	2.68	34.55	5.98	7.77	9.46	8.32	31.26
10	0.36-0.40	0.00	0.08	0.48	0.56	9.10	26.86	22.05	40.88
10	0.57-0.61	0.00	0.06	0.51	0.02	8.10	18.25	12.16	50.90
9	1.41-1.45	0.00	0.30	6.28	3.38	6.37	13.39	13.39	56.89
9	1.72-1.76	0.00	0.99	9.18	3.45	5.36	13.04	11.80	56.19
9	2.03-2.07	0.00	1.69	18.68	4.61	5.26	11.06	10.49	48.20
8	2.42-2.46	0.00	1.42	15.47	5.18	11.08	19.57	14.02	33.26
7	2.51-2.55	0.00	8.33	63.69	9.12	2.31	3.06	2.76	10.73

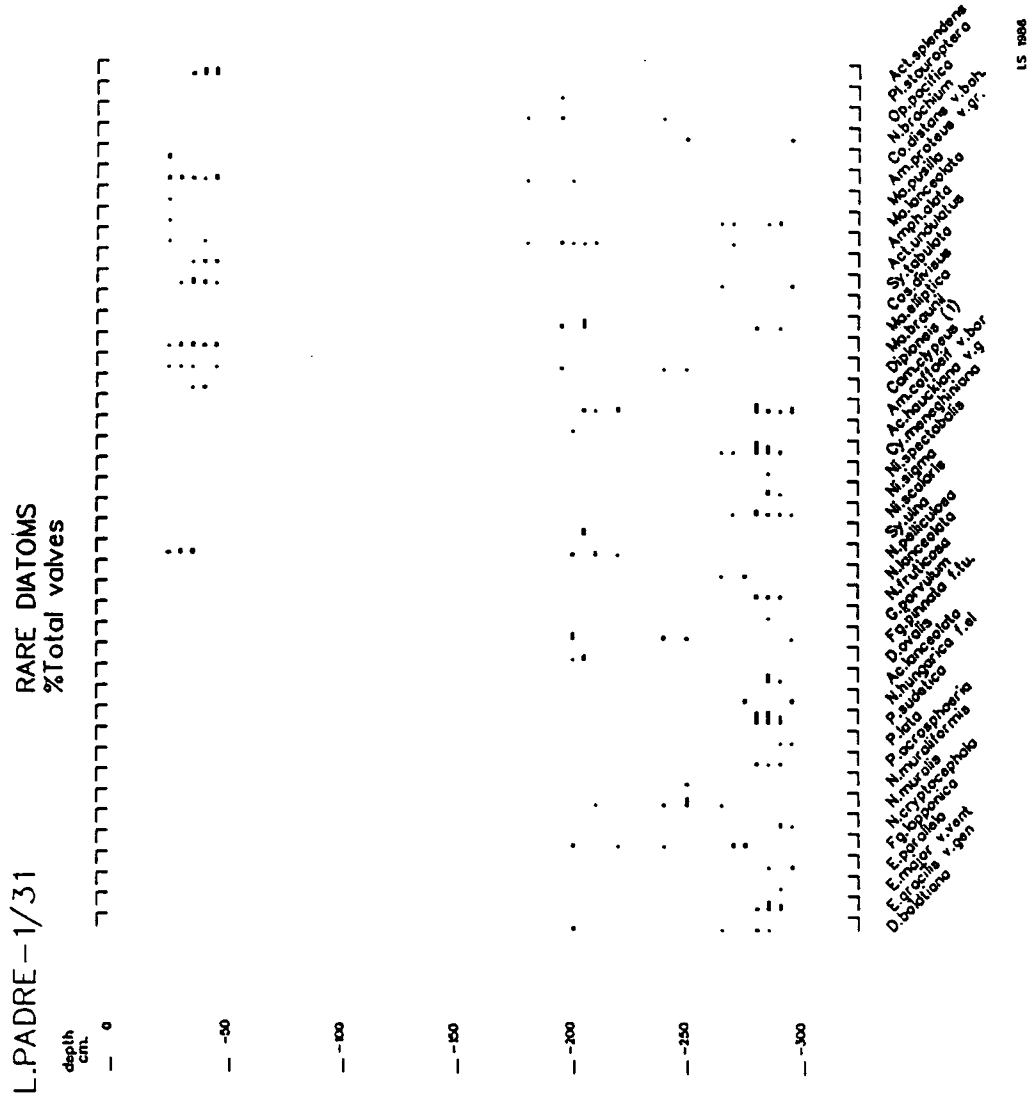
Particle size analysis

Stratum	Depth (m)	Gravel (%)	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Medium silt (%)	Fine silt (%)	Clay (%)
5	3.08-3.12	0.00	0.32	0.63	0.42	14.75	44.60	23.42	14.87
4	3.24-3.28	0.00	0.17	0.97	1.31	16.11	31.94	23.31	26.18
3	3.56-3.60	0.00	0.66	1.48	0.89	14.80	40.53	26.03	15.62
3	3.82-3.86	0.00	1.22	5.83	1.51	15.32	36.25	23.56	16.31
1	5.00-5.04	0.00	4.19	21.40	6.13	11.84	16.40	11.98	28.06

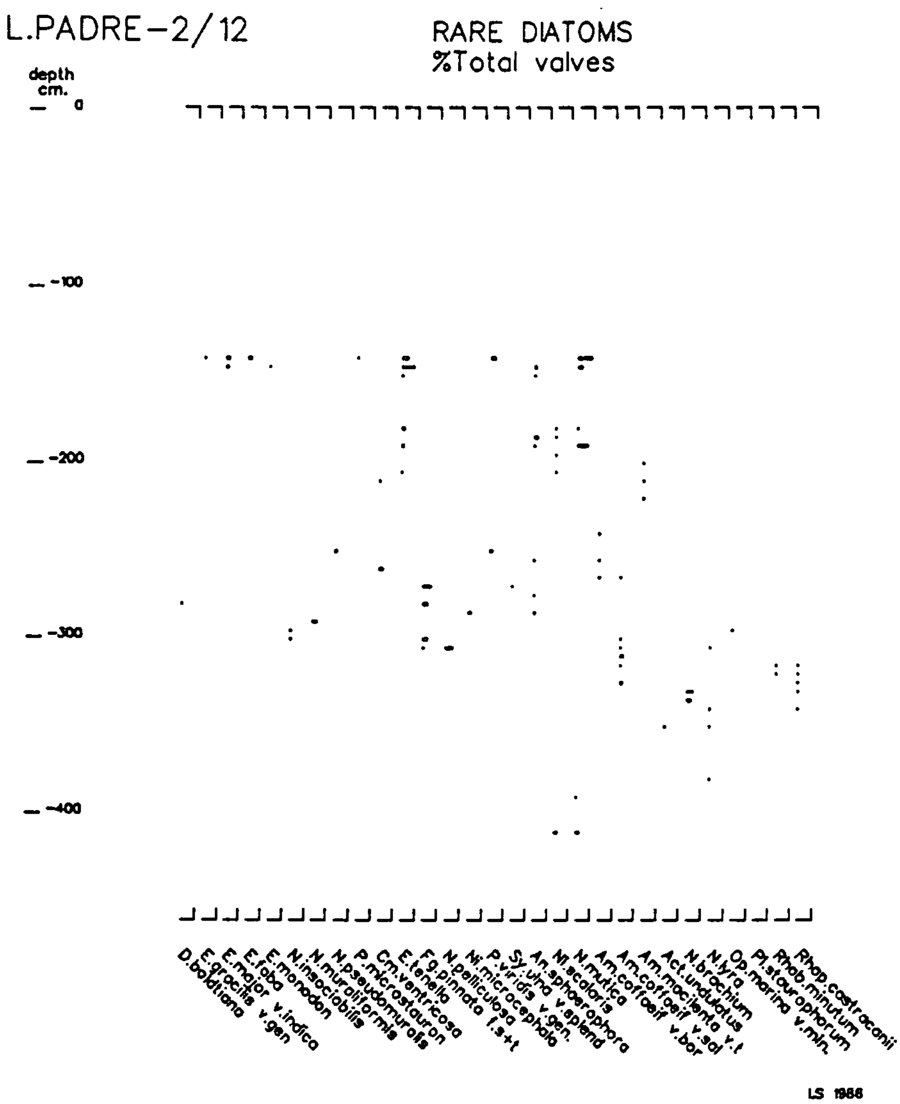
Appendix IV

Rare diatoms encountered in the study

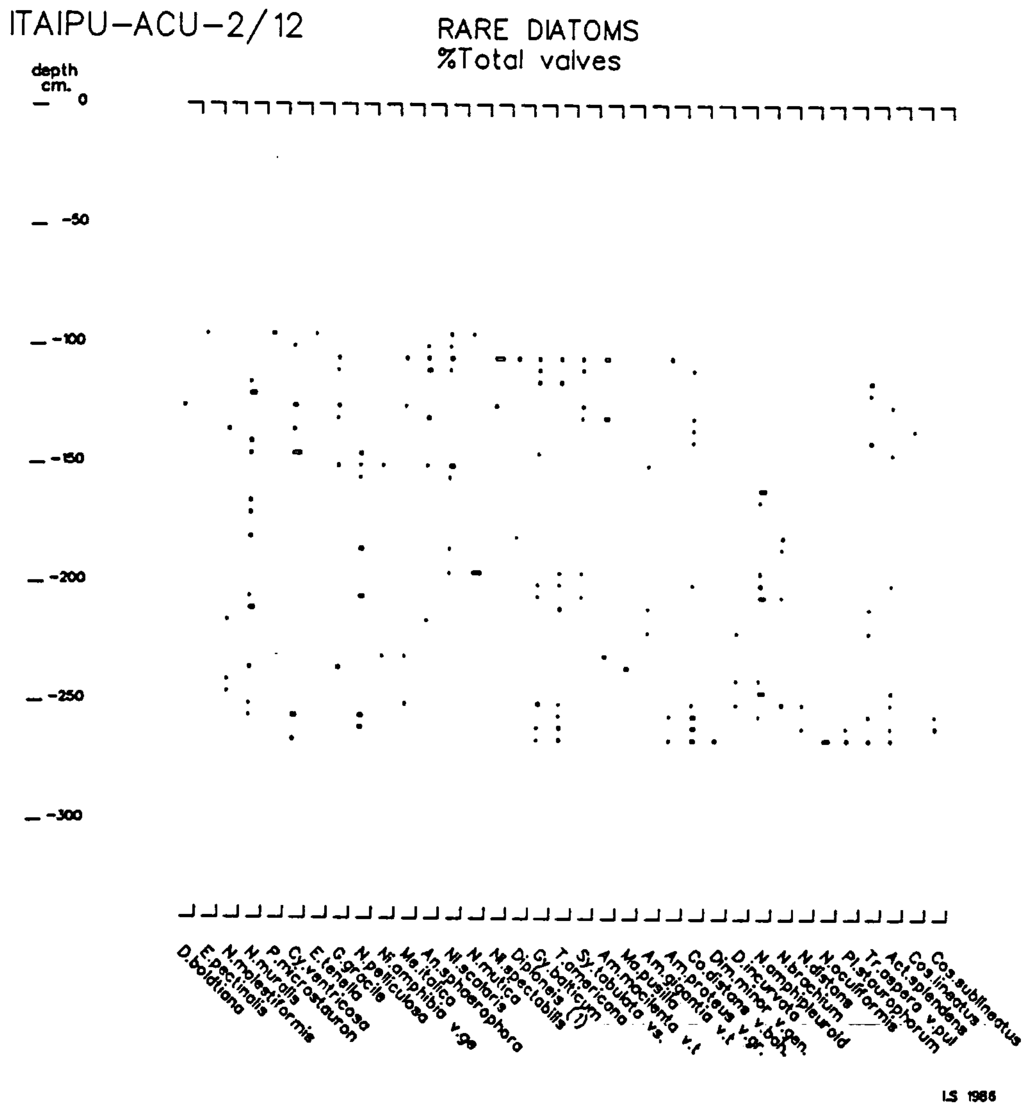


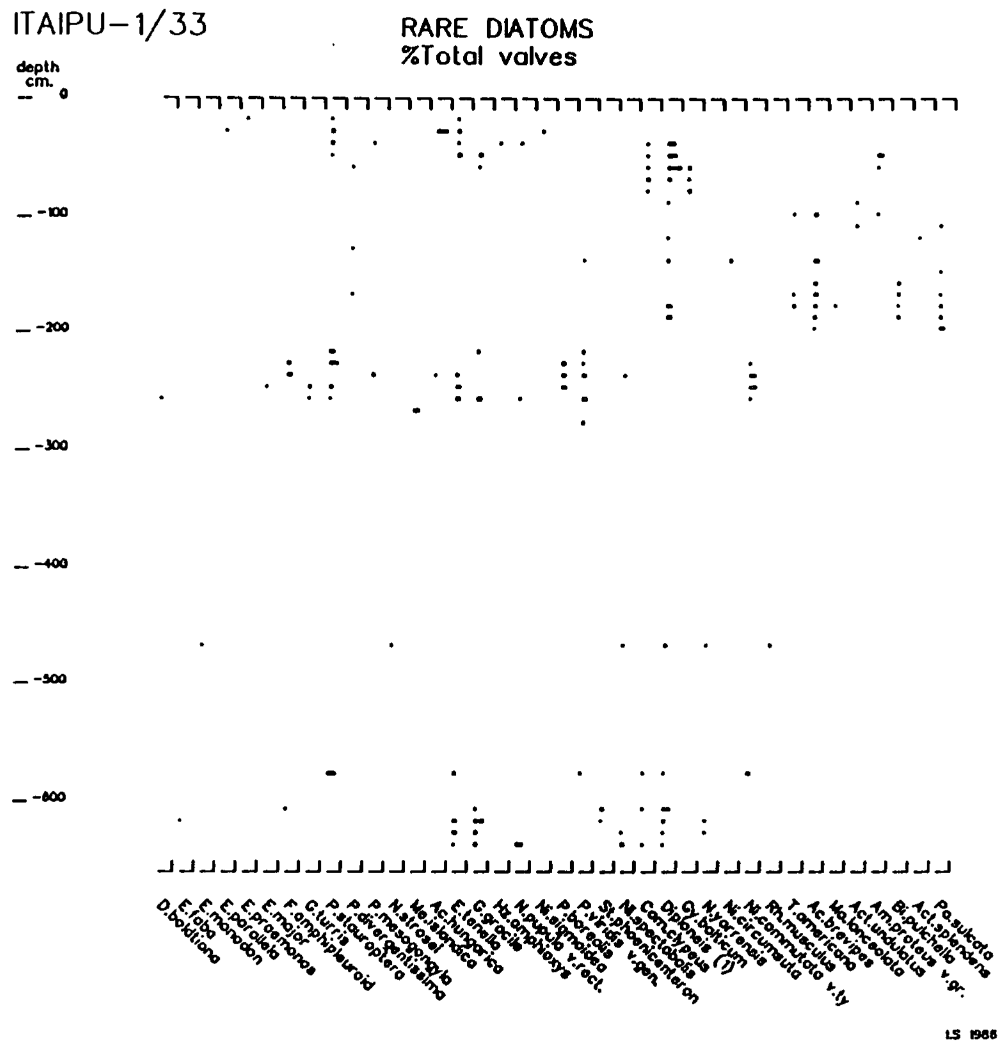


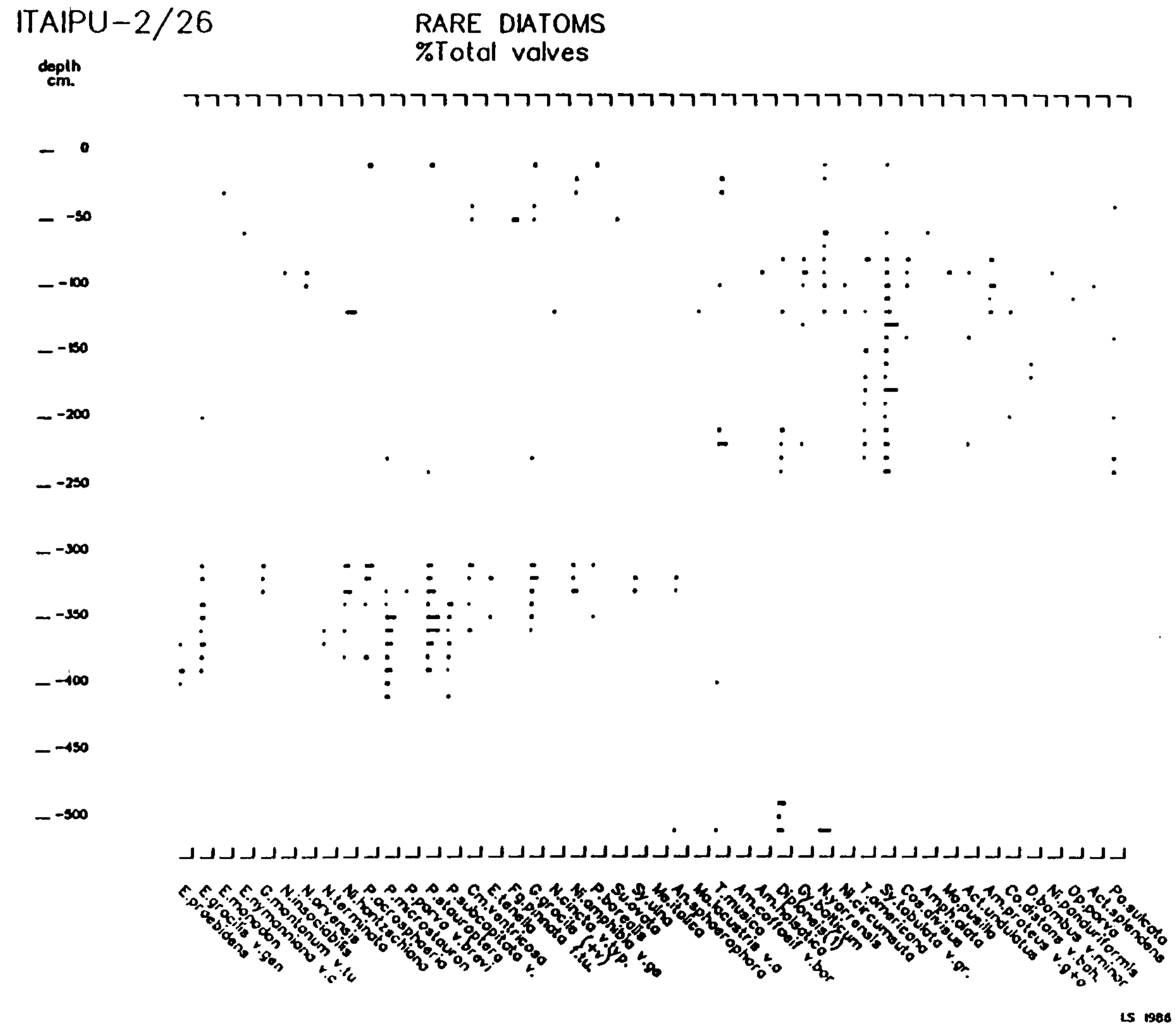
L.PADRE – 1/31
RARE DIATOMS
%Total valves
depth cm.
0
-50
-100
-150
-200
-250
-300
LS 1986



L.PADRE-2/12
RARE DIATOMS
%Total valves
depth
cm.
0
-100
-200
-300
-400
D.boldtiana
E.gracilis v.gen
E.major v.indica
E.faba
E.monodon
N.insociabilis
N.muraliformis
N.pseudomuralis
P.microstauron
Cm.ventricosa
E.tenella
Fg.pinnata f.s+t
N.pelliculosa
Ni.microcephala
P.viridis v.gen.
Sy.ulna v.splend
An.sphaerophora
Ni.scalaris
N.mutica
Am.coffaeif
Am.coffaeif v.bor
Am.macilenta v.sal
Act.undulatus v.t
N.brachium
N.lyra
Op.marina v.min.
Pl.staurophorum
Rhob.minutum
Rhop.castracanii
LS 1986


ITAIPU–ACU–2/12
RARE DIATOMS
%Total valves
depth cm.
0
-50
-100
-150
-200
-250
-300
D.boldtiana
E.pectinalis
N.molestiformis
N.muralis
P.microstauron
Cy.ventricosa
E.tenella
G.gracile
N.pelliculosa
Ni.amphibia v.ge
Ma.italica
An.sphaerophora
Ni.scalaris
N.mutica
Ni.spectabilis
Diploneis (?)
Gy.balticum
T.americana
Sy.tabulata v.s.
Am.macilenta v.t
Ma.pusilla
Am.gigantia v.t
Am.proteus v.gr.
Co.distans v.bot.
Dim.minor v.gen.
D.incurvata
N.amphipleuroid
N.brachium
N.distans
N.oculiformis
Pl.staurophorum
Tr.aspera v.pul
Act.splendens
Cos.lineatus
Cos.sublineatus
LS 1986

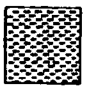

ITAIPU–1/33
RARE DIATOMS
%Total valves
depth
cm.
0
-100
-200
-300
-400
-500
-600
D.boldtiana
E.faba
E.monodon
E.paralela
E.praemonos
E.major
F.amphipleuroid
G.turris
P.stauroptera
P.divergentissima
P.mesogongyla
N.stroesei
Me.islandica
Ac.hungarica
E.tenella
G.gracile
Hz.amphioxys
N.pupula v.rect.
N.sigmoidea
P.borealis
P.viridis v.gen.
St.phoenicenteron
N.spectabilis
Cam.clypeus
Diploneis (?)
Gy.balticum
N.yarrensis
N.circumsuta
N.commutata v.ty
Rh.musculus
T.americana
Ac.brevipes
Ma.lanceolata
Act.undulatus
Am.proteus v.gr.
Bi.pulchella
Act.splendens
Pa.sulcata
LS 1988


ITAIPU-2/26
RARE DIATOMS
%Total valves
depth cm.
0
-50
-100
-150
-200
-250
-300
-350
-400
-450
-500
E.praebidens
E.gracilis v.gen
E.monodon
E.nymanniana v.c
G.montanum v.tu
N.insociabilis
N.arvensis
N.terminata
Ni.hantzschiana
P.acrosphaeria
P.microstauron
P.parva v.brevi
P.stauroptera
P.subcapitata v.
Cm.ventricosa
E.tenella
Fg.pinnata f.tu.
G.gracile (+v)
N.cincta v.typ.
Ni.amphibia v.ge
P.borealis
Su.ovata
Sy.ulna
Me.italica
An.sphaerophora
Mo.lacustris v.a
T.musica
Am.coffaeif v.bor
Am.holsatica
Diploneis(?)
Gy.balticum
N.yarrensis
Ni.circumsuta
T.americana
Sy.tabulata v.gr.
Cos.divisus
Amph.alata
Mo.pusilla
Act.undulatus
Am.proteus v.g+o
Co.distans v.bah.
D.bombus v.minor
Ni.panduriformis
Op.parva
Act.splendens
Po.sulcata
LS 1986

Appendix V

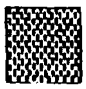
Key to the stratigraphic symbols

The symbols shown below follow the scheme devised by Troels-Smith (1955). The original paper should be consulted for a comprehensive key of the symbols used.



$\mathrm{Sh}^{4}4$
Substantia humosa
(Undiff. organic material)

$\mathrm{Th}^{4}4$
Turfa herbacea
(Roots of herbaceous plants)



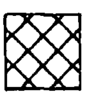
$\mathrm{Th}^{3}4$
Turfa herbacea
(Roots of herbaceous plants)

$\mathrm{Tl}^{3}4$
Turfa lignosa
(Roots of woody plants)

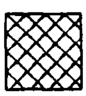
Dh1
Detritus herbosus
(Herbaceous fragments > 2mm)

Dl1
Detritus lignosus
(Woody fragments > 2mm)

Dg2
Detritus granosus
(Plant fragments from 0.1 to 2 mm)

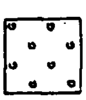


$\mathrm{Ld}^{3}2$
Limus humosus c. detritu
(Fine detritus mud)

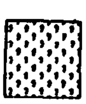


$\mathrm{Ld}^{1}3$
Limus detrituosus c. humo
(Fine detritus mud)

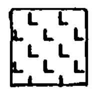
anth 4
anthrax
(Charcoal)



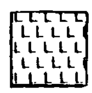
test. (moll.) 2
testae (molluscorum)
(Whole mollusc shells)



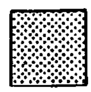
part. test. (moll.) 4
particulae testarum (molluscorum)
(Mollusc shell fragments)



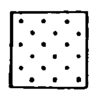
As2
Argilla steatodes
(Clay)



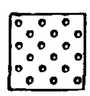
Ag3
Argilla granuosa
(Silt)



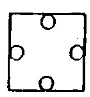
Ga4
Grana arenosa
(Fine and medium sand)



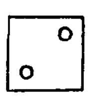
Gs3
Grana saburralia
(Coarse sand)



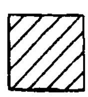
Gg (min.) 3
Grana glareosa (minora)
(Fine gravel)



Gg (maj.) 2
Grana glareosa (majora)
(Medium gravel)



Gg (max.) 1
Grana glareosa (maxima)
(Coarse gravel)



Str. Conf.
stratum confusum
(Disturbed stratum)

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lim. 1
limes diffusus
(Boundary area 2mm to 1 cm)

lim. 2
limes conspicuus
(Boundary area 1 to 2 mm)

lim.3
limes manifestus
(Boundary area 0.5 to 1 mm)

lim 4
limes acutus
(Boundary area < 0.5 mm)

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